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# Mercury emissions during collection and disposal of lamps

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## Abstract

For their functioning, gas-discharge lamps, which include compact fluorescent lamps and fluorescent tubes among others, need mercury. Used ("burnt-out") lamps therefore have to be disposed of separately from domestic waste. The article reports on a project of the social accident insurance institutions to obtain information on collection practice with used lamps and on the recycling of flat screens with their cold-cathode fluorescent lamps by interviewing the persons concerned. Concurrently, the project replicated activities with lamps in a test chamber and measured the mercury concentration. It investigated the level of mercury emissions that can arise on breakage of cold-cathode fluorescent tubes removed from flat screens. Furthermore, it also determined the mercury exposure that can arise during the collection of used lamps and during their replacement when they break in the process. Also tested were protective measures for reducing mercury exposure.

## Quecksilberemissionen bei der Sammlung und Entsorgung von Leuchtmitteln

### Zusammenfassung

Gasentladungslampen, dazu gehören unter anderem Kompaktleuchtstofflampen und Leuchtstoffröhren, benötigen zu ihrer Funktion Quecksilber. Gebrauchte („ausgebrannte") Lampen müssen deshalb getrennt vom Hausmüll entsorgt werden. Der Beitrag berichtet über ein Projekt der Unfallversicherungsträger, das zum Ziel hatte, mittels Befragung Informationen zu erhalten zur Sammelpraxis von gebrauchten Leuchtmitteln und zum Recycling von Flachbildschirmen mit deren Kaltkathoden-Leuchtstofflampen. Parallel dazu wurden Tätigkei-

ten mit Leuchtmitteln in einer Prüfkammer nachgestellt und die Quecksilberkonzentration gemessen. Untersucht wurde, welche Quecksilberemissionen beim Bruch von Kaltkathoden-Leuchtstoffröhrchen, die aus Flachbildschirmen ausgebaut werden, auftreten können. Ferner wurde die Quecksilberexposition ermittelt, die bei der Sammlung von gebrauchten Leuchtmitteln und bei deren Wechseln auftreten kann, wenn diese dabei zerbrechen. Zusätzlich wurden Schutzmaßnahmen zur Reduzierung der Quecksilberexposition getestet.

## 1 Introduction

The European Union has formulated requirements concerning the energy efficiency, functionality and product information of certain lamps in two regulations [1; 2]. Lamps which do not satisfy these efficiency requirements may no longer be placed on the market. One consequence of this was that compact fluorescent lamps (CFLs) were increasingly replacing traditional incandescent light bulbs[1].

Like fluorescent tubes, end-of-life CFLs constitute electronic waste in Germany under the German Electrical and Electronic Equipment Act (ElektroG). This act transposed the EU WEEE Directive on waste electrical and electronic equipment and the RoHS Directive restricting the use of hazardous substances in electrical and electronic equipment [3] into German law in March 2006. With adoption of the RoHS Directive, restrictions now apply to the content of substances such as mercury in electrical and electronic equipment which is placed on the market for the first time. Exemptions to these restrictions are stated in the annex of the RoHS Directive. These include the use of mercury in lamps, the maximum permissible quantities of which are being progressively lowered. Since September 2010, it has been a requirement for the mercury content of new lamps placed on the market to be stated on the products' packaging. For example, the maximum permissible mercury content of a CFL with a rating of < 30 W was 3.5 milligram (mg), falling to 2.5 mg in 2013. CFLs with a mercury content substantially below these limits (e.g. 1.5 mg) are already available on the market. Since January 2012, the maximum permissible mercury content of standard straight fluorescent tubes has been between 3.5 and 7 mg. High-pressure mercury vapour lamps currently contain up to 30 mg of mercury. The exemption for these products ends in April 2015. These lamps will therefore also disappear from the market. High-pressure mercury vapour lamps consume considerably more electricity than other high-pressure lamps [4].

For the sake of comparison: clinical thermometers may contain between 500 and 3,000 mg of mercury, barometers approximately 1,000 to 3,000 mg, and older blood-pressure gauges as much as 150,000 mg [5 to 7].

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[1] Nowadays there is a trend to LED. The replacement of CFLs and so the waste is already increasing.

The German Electrical and Electronic Equipment Act (ElektroG) also governs the collection of end-of-life CFLs, fluorescent tubes and high-pressure mercury vapour lamps, and end-of-life electronic equipment. This includes cold-cathode fluorescent lamps used for backlighting in end-of-life flat TV sets and computer monitors. Private and commercial users must dispose of these products separately from domestic refuse. Under Section 9 of the ElektroG, municipal and district authorities are required to set up collection points for these products. Manufacturers have been obliged for several decades to accept end-of-life fluorescent tubes for disposal.

## 2 Principle of operation of fluorescent lamps

Like fluorescent tubes, CFLs are low-pressure gas-discharge lamps comprising one or more short curved or helical glass tubes. They contain argon or a mixture of argon and krypton, a small quantity of mercury, and on the inside surface, a luminescent substance containing a small quantity of rare earths. In the past, mercury in metallic (liquid) form was used in the fluorescent lamps. It is now incorporated into the lamp in the form of a small mercury/iron pellet or as an amalgam. When the lamp is switched on, part of the mercury vaporizes, filling the entire jacket of the lamp with the mercury vapour required for discharge. The potential difference between the electrodes generates a flow of electrons which excites the mercury atoms, in turn causing them to emit UV radiation. The luminescent material on the walls of the glass tubes converts this radiation into visible light [8; 9].

## 3 Provisions governing hazardous substances

In accordance with EU Regulation 1272/2008 on the classification, labelling and packaging of substances and mixtures (CLP Regulation), mercury is classified as shown in **Table 1** [10]. Mercury must also be marked with the signal word "Danger".

**Table 1:**
**Classification and labeling of mercury under the CLP Regulation**

| Hazard class | Hazard category | H statement |
|---|---|---|
| Acute toxicity, inhalation | Cat. 2 | H330, Fatal if inhaled |
| Reprotoxicity | Cat. 1B | H360D, May damage the unborn child |
| Specific target organ toxicity (repeated exposure) | Cat. 1 | H372, Causes damage to organs through prolonged or repeated exposure |
| Acute/chronic aquatic hazard | Cat. 1 | H400, Very toxic to aquatic life<br>H410, Very toxic to aquatic life with long lasting effects |

No OSH regulations specific to mercury and its combinations are in force in Germany; the German Ordinance on hazardous substances applies. The Technical Rule for Hazardous Substances (Technische Regel für Gefahrstoffe, TRGS) 900 (occupational exposure limits, OELs) state an OEL of 20 microgram per cubic metre (µg/m³, 0.02 mg/m³) for mercury and its inorganic compounds. A level of eight times this value (160 µg/m³) must not be exceeded over brief durations (15-minute mean, peak limit Category II) [11].

The TRGS 903 (biological limit values) specify a limit value of 25 µg of mercury per gram of creatinine [12].

## 4 Routes of exposure in the human body

Mercury is the only metal that is liquid at room temperature, and exhibits a relatively high vapour pressure. Metallic mercury thus easily transitions to the vapour phase and is readily absorbed via the lungs. The absorption rate through this exposure route is approximately 80%. Conversely, the uptake of metallic mercury through the skin and the gastrointestinal tract is negligible. Approximately 2 to 15% of inorganic mercury compounds in vegetable foodstuffs are absorbed in the intestine. By contrast, organic mercury compounds, such as methyl mercury encountered in fish food products, are absorbed almost entirely in the gastro-intestinal tract. According to information from the World Health Organization (WHO), the total quantity of mercury in the body is attributable essentially to uptake via dental amalgam and fish foodstuffs, owing to the low absorption rate of inorganic mercury compounds [13].

## 5 Background exposure

As early as 1999, the Human Biomonitoring Commission at the German Federal Environment Agency (Umweltbundesamt, UBA) drew attention in its substance monograph on mercury to natural mercury emissions in the environment caused by volcanic activity, weathering of rock, and vapour emissions from the earth's crust and oceans. Anthropogenic sources of outdoor atmospheric exposure are the combustion of fossile fuels, for example during power generation from coal; the smelting of sulphide ores; cement production; waste incineration; and in the past, the use of mercury compounds in agriculture. Mercury is also released as a by-product during the recovery of crude oil/natural gas. In Germany, the atmospheric background concentration lies between 2 and 4 nanogram per cubic metre (ng/m³); it may reach 10 ng/m³ in urban areas [14]. The ad-hoc working group of the Indoor Air Hygiene Commission (Innenraumlufthygienekommission, IRK) at the UBA and the working group of the higher state health authorities (Arbeitsgemeinschaft der Obersten Landesgesundheitsbehörden, AOLG) has set out guideline values for substances in the indoor atmosphere in non-commercially used indoor areas. The guide value II (RW II, an effect-related value) for mercury is 0.35 µg/m³ (350 ng/m³) and the guide value I (RW I, the precautionary guide value) is 0.035 µg/m³ (35 ng/m³). No results of systematic measurements in indoor areas are available. Atmospheric mercury concentrations of up to 70 µg/m³ were measured in living accommodation previously used as workshops for the coating of mirrors. Indoor mercury concentrations of up to 10 µg/m³ were measured in the USA as a result of the use of latex coatings containing preservatives in the form of phenylmercury acetate. Studies conducted by the Bavarian Health and Food Safety Authority (Bayerisches Landesamt für Gesundheit und Lebensmittelsicherheit, LGL) in 2011 of its own laboratory and office premises revealed mercury concentrations of 5 to 50 ng/m³ (with an average of 15 ng/m³) [5; 6; 13].

## 6 Activities of the German Social Accident Insurance Institutions

The German Social Accident Insurance (Deutsche Gesetzliche Unfallversicherung, DGUV) established a working group under the overall control of the German Social Accident Insurance Institution for the public sector in Hesse (UKH). Members of the working group are:

- German Social Accident Insurance Institution for the health and welfare services (Berufsgenossenschaft für Gesundheitsdienst und Wohlfahrtspflege, BGW)
- German Social Accident Insurance Institution for the energy textile electrical and media products sectors (Berufsgenossenschaft Energie Textil Elektro Medienerzeugnisse, BG ETEM)
- German Social Accident Insurance Institution for the trade and distribution industry (Berufsgenossenschaft Handel und Warenlogistik, BGHW)
- German Social Accident Insurance Institution for the administrative sector (Verwaltungs-Berufsgenossenschaft, VBG)
- German Social Accident Insurance Institution for the transport industry (Berufsgenossenschaft für Transport und Verkehrswirtschaft, BG Verkehr)
- German Social Accident Insurance Institution for the public sector in North Rhine-Westphalia (Unfallkasse Nordrhein-Westfalen, UK NRW)
- German Social Accident Insurance Institution for the public sector in Rhineland-Palatinate (Unfallkasse Rheinland-Pfalz, UK RLP)
- German Social Accident Insurance Institution for Deutsche Post and Deutsche Telekom (Unfallkasse Post und Telekom, UKPT)
- Association of German Social Accident Insurance Institutions for local authorities in Hanover (Gemeindeunfallversicherungsverband Hannover, GUVH)
- Institute for Occupational Safety and Health of the German Social Accident Insurance (Institut für Arbeitsschutz der DGUV, IFA)

- Zentralverband Elektrotechnik und Elektronikindustrie e.V. – Fachverband Elektrische Lampen (German Electrical and Electronic Manufacturers' Association – Lighting Division)
- Association of German municipal companies (Verband der kommunalen Unternehmen, VkU)

A chief function of the working group was to identify processes and tasks associated with exposure to mercury. Mercury and its inorganic compounds are primarily used in the production of lamps and electronic signage. Mercury may be released during the collection of end-of-life lamps when lamps break or are delivered to collection points when already broken. Mercury may also be released from broken fluorescent tubes during the disassembly of flat TV screens and computer monitors. Lamps containing mercury must be recycled. The recycling process includes recovery of the mercury. The processes used may give rise to mercury emissions.

## *6.1 Questionnaire survey by the German Statutory Accident Insurance Institution for the public sector*

Since insufficient information was available on the methods for collection of end-of-life lamps, further information was gathered by means of a questionnaire survey conducted in representative large companies in the public sector (**Table 2**). Eight accident insurance institutions were involved and 86 questionnaires evaluated.

**Table 2:**
**Institutions surveyed by the German Social Accident Insurance Institutions for the public sector (multiple choice possible)**

| Type of enterprise | Share in % |
|---|---|
| Waste disposer | 22.0 |
| Builder's depot/recycling centre | 58.0 |
| Job creation association | 2.2 |
| University | 6.6 |
| Clinic | 2.6 |
| Prison service | 1.8 |
| Municipal administration | 1.3 |
| Other enterprise | 1.3 |
| Mobile hazardous waste vehicle | 4.4 |

80% of the collection points were waste disposal plants and their recycling depots (builder's depots) and mobile collection facilities. Flat screens and monitors were collected in 95% of the companies. Screens were disassembled and cold-cathode fluorescent lamps removed in specialized companies (see Section 6.2) or in public-sector job-creation associations.

Standard fluorescent tubes were generally collected on post pallets (**Figure 1**), CFLs and fluorescent tubes of non-standard geometry in open mesh boxes (**Figure 2**). Closed plastic (60/150 l) or metal (**Figures 3 and 4**) bins were however also used.

**Figure 1:**
**Post pallet**

**Figure 2:**
**Mesh box**

**Figure 3:**
**Plastic bin**

**Figure 4:**
**Metal bin**

Over three-quarters of all companies stored the end-of-life products in the open-air or in open or semi-open (i.e. fully ventilated) halls. Nine percent of the companies consulted gave no indication of where the collecting containers were located. Only the companies with mobile collection points (collection vehicles) indicated that these were equipped with mechanical ventilation systems, with five-fold air exchange. The requirements for the technical equipment of collection vehicles are formulated in the TRGS 520 [15].

The responses to the question of the risk assessment in accordance with the TRGS 400 were notable [16]: in almost 80% of cases, no risk assessment was available, it was regarded as "not applicable", or no answer was given. Only 3.9% of the companies indicated that mercury measurements had already been conducted in relation to the collection of end-of-life lamps. The response to the question concerning biomonitoring was similar.

One to two workers per shift were generally employed at the collection points; these employees accepted end-of-life lamps in addition to other recyclable materials. The end-of-life products were generally placed in the collection bins by the customers themselves; the personnel merely provided information and had supervisory functions. Accordingly, the responses to the question of exposure to mercury differed widely, from the full length of the shift, through one to two hours or less than 30 minutes per shift, to "zero exposure". Given that it takes less than one minute to place one or even several CFLs in a bin, it can be seen that the actual exposure duration per shift will be in the order of minutes and will in no way exceed an hour, even when large quantities are delivered.

The answers concerning the quantities of end-of-life lamps differed widely. Some companies indicated the quantities in tons per year, others in the number of individual lamps per week, month or year. The quantity of CFLs for example differed between five and seven lamps per day, that of fluorescent tubes between ten and a hundred tubes. The quantities of lamps to be disposed of, particularly CFLs, will increase substantially in the future as the use of such lamps increases. Employees at the recycling depots stated that only a small proportion (around 1%) of the end-of-life lamps supplied were broken.

### *6.2 Surveys concerning the recycling of flat screens and monitors in sheltered workshops*

The flat screens and monitors currently delivered for recycling contain cold-cathode fluorescent lamps (CCFLs) with multiple mini fluorescent tubes containing mercury. The level of exposure arising during disassembly of the screens is not currently known. By around 2020, however, the recycling volumes of products employing CCFL technology are expected to become substantial [17]. Objective estimation of the exposure is therefore necessary. Such estimations should be based upon the typical working conditions at recycling workplaces. The BGW therefore surveyed specialized sheltered workshops regarding the recycling of flat screens and monitors. Three sheltered workshops were first inspected and seven sheltered workshops surveyed regarding the process parameters of flat screen and monitor recycling that are relevant to exposure. Answers were sought to questions concerning the disassembly procedure, tube breakage at delivery and during disassembly, and the general conditions in the plant such as the size of rooms, number of workstations, and ventilation arrangements. The association of sheltered workshops (Gesellschaft der Werkstätten, GDW) and the association of recycling companies (Recyclingpartner-Gesellschaft, RPG) supported the BGW in this task. Owing to the low quantities of data, the survey does not claim to be representative; instead, the aim was merely to identify a trend in advance of the planned workplace measurements.

### *6.3 Results*

The surveys regarding the parameters relevant to exposure during the disassembly of flat screens and monitors were conducted at the beginning of 2012 in seven sheltered workshops (**Table 3**).

**Table 3:**
**Results of survey: parameters relevant to exposure during manual disassembly of flat screens and monitors**

| Enterprise | A | B | C | D (1) | D (2) | E | F | G |
|---|---|---|---|---|---|---|---|---|
| Monitored period (MP) | 17. to 21.02.12 | MP 1[4]: 04.01. to 24.01.12 MP 2[5]: 25.01. to 27.02.12 | January 2012 | January 2012 | 21.06. 2012 | January 2012 | January 2012 | January 2012 |
| Volume in $m^3$ | N/A [3] | N/A | 1,600 | 1,200 | 1,200 | 1,800 | 4,500 | 2,000 |
| Type of ventilation[1][2] | NV | NV | NV | NV | NV | NV | MV | NV |
| Number of disassembled LCD units/ shift (current) | 45 in MP | N/A | 3 | N/A | 18 PCs 8 TVs | 8 | 1 | 1 |
| Disassembly capacity/shift (estimate for the future) | N/A | N/A | 6 | > 20 | > 20 | 12 | 20 | 20 |
| Removed tubes | 193 in MP | 139 in MP 1[4] 208 in MP 2[5] | N/A | N/A | 102 (PCs) 240 (TVs) | N/A | N/A | N/A |
| Breakage on delivery in % | 1.7 | N/A | < 10 | < 5 | < 2 | 10 | 10 | 1 |
| Breakage during disassembly in % | < 3 | 50 [4] 11 [5] | 1 per day | < 1 | < 1 | 10 to 15 | 1 to 50 | > 2 |
| Breakage into x pieces (disassembly) | x = 2 | x > 2[4] x = 2[5] | x = 2 | x = 2 | x = 2 | x = 2 | N/A | x = 2 |
| Disassembly depth [6] | C | C[4]/SA[5] | SA | SA | SA (PCs)/ C (TVs) | C | SA | N/A |

1) No workplace extractor fans in any work areas.
2) NV: natural ventilation, MV: mechanical ventilation
3) N/A: no answer
4) Test phase, tubes removed from mountings
5) Routine phase, tubes left in mountings
6) SA: sub-assembly = tubes remain in mounting; C: component = tube forms a single glass body

In one sheltered workshop, the BGW observed the dismantling processes over an entire working shift. The results showed in the first instance that the process of flat screen and monitor disassembly in the workshops is still in its infancy. Owing to the particular responsibility of sheltered workshops for their staff and the uncertainty regarding what protective measures are necessary, the products are currently collected and stored, but are disassembled routinely only on a small scale.

The workplaces are generally divided into disassembly areas in which other electronic waste is also broken up. Ventilation is normally natural, via windows and doors. Arrangements for workplace fume exhaust are not provided. TV screens and computer monitors constitute the products that are disassembled. Outside tube diameters of 2 to 4 mm were stated, and tube lengths of 20 to 120 cm. A single flat TV screen contains up to 32 mini fluorescent tubes. In TV screens, the tubes are arranged over the entire area behind the front LCD screen, and must be removed individually. This is achieved by cutting open of the plastic mountings by means of pincers, and retrieval of the tubes. Computer screens contain between four and eight miniature fluorescent tubes in two mountings behind the front LCD screen. Depending upon the procedures in the plant, the tubes are left in their mountings and placed in interim storage, or removed from the mountings. The latter increases the risk of breakage. Broken tubes are the only relevant source of mercury emissions at the disassembly workplaces. Particular attention was therefore paid to the breakage rate. Five workshop managers estimated the breakage rate at delivery to be between 1 and 10%. One plant documented the breakage rate at delivery precisely; it was around 1.7%. One of the companies provided no answer to this question. According to the companies, the breakage rate during disassembly lay between < 1 and 50%. The breakage rate of 50% was attributed to a disassembly test phase and inexperience on the part of the workers. During this test phase, the tubes broke into more than two pieces during the disassembly of computer monitors and retrieval of the tubes from the mountings. A breakage rate of 11% was stated for the subsequent routine phase; during this phase, the tubes broke into two pieces. In the other plants, tubes broke almost exclusively into two pieces during disassembly. The data relating to disassembly were also documented precisely in the workshop conducting its own monitoring (D (2) in Table 3). In this case, the breakage rate was < 2%. Here too, the tubes broke into two pieces.

Experience in the sheltered workshops shows that gentle, non-destructive collection and delivery reduces damage to the end-of-life products prior to disassembly to a minimum. During disassembly itself, a breakage rate of tubes of below 5% appears to be attainable without difficulty when the work is performed by personnel who have received instruction. This means that on one TV screen in two, i.e. approximately once an hour, one or two tubes each break into two parts.

## 7 Simulated studies in a test chamber

Parallel to the surveys conducted by the accident insurance institutions, tests were conducted by the IFA in a test chamber in conjunction with the UKH and the BGW. The tests were based upon simulated scenarios in which lamps containing mercury were broken at workplaces, together with tasks that can frequently be observed during the collection and disposal of end-of-life lamps. They were supplemented by series of tests in which brand-new and end-of-life lamps of different brands and types were broken in a floor trough. The release of mercury vapour was to be measured in the following indoor scenario: lamp change involving lamp breakage, followed by sweeping up and disposal of the fragments contaminated with mercury. Trends for a possible hazard were to be identified by comparison with the current OELs for mercury.

The test chamber had a volume of 42 m³ and a surface area of 4.00 m × 3.50 m. The walls were faced almost completely with smooth plastic. Four vents in the ceiling and another four in the floor area enabled the air volume to be exchanged up to 15 times per hour. During the measurements, the climate parameters of the atmosphere in the test chamber exhibited a room temperature of between 23 and 25 °C and a relative atmospheric humidity of 45 to 60%. Unless stated otherwise in the table of results, the simulated exposures were performed under worst-case conditions, i.e. with mechanical ventilation switched off in the test chamber, which was relatively well sealed. This corresponds to natural ventilation with an air-exchange rate of approximately 0.5 times per hour.

Wherever possible, the mercury vapour measurements in the tests were performed simultaneously by means of two direct-reading meters (monitors), calibrated in advance and featuring integrated sample air pumps and teflon dust filters. Teflon hoses mounted on stands fed sampling air to the mercury monitors for analysis. The air was sampled both just above the rims of collecting bins/a floor trough, and in the theoretical breathing air region of the workers, for example at a height of 1.50 m above the mercury emission source. The concentration characteristics were recorded by plotters and saved simultaneously in a data logger.

The following UV photometric gas meters were employed for continuous measurement of the mercury vapour concentration in workplace atmospheres: Environmental Process Monitoring 791.905 and Seefelder Messtechnik Hg-Monitor 2000. The meters had a mercury measuring range of 0 to 2 000 µg/m³ and a detection limit of ≤ 2 µg of mercury per m³. The IFA's 8530 standard measurement method [18] was also used as a reference method for validation of the measurement methods, particularly during the analysis of low mercury concentrations.

## *7.1 Release of mercury during the disassembly of LCD flat screens and monitors*

The BGW supplied the IFA with test material from recycling plants. The CCFL tubes were first removed carefully from their metal receptacles. Drop tests were then performed from a height of 1.20 m onto a metal plate in order to determine how the tubes broke. These findings served as a basis for subsequent detailed study of a range of forms of breakage – simple, multiple and completely crushed – in a 13-litre glass vessel. The breakage form of complete crushing was intended to simulate a tube being crushed underfoot at the workplace.

During the studies in the standardized 13-litre vessel, the sample flow of the direct-reading mercury monitor travelled in a loop, i.e. without losses, both through the standardized vessel containing the tube fragments, and through the measurement cuvette in the meter. This test arrangement enabled the characteristic of the mercury concentration in the vessel to be observed over a period of up to 16 hours. **Table 4** shows the results of the breakage-test studies performed on CCFL fluorescent tubes in the standardized 13-litre vessel.

**Table 4:**
**Measurement results of the release of mercury during breakage of CCFL fluorescent tubes**

| Manufacturer | Length in mm | Mass in g | Measurement duration in h | Hg concentration measured in vessel in µg/m³ | Hg quantity released from tube in µg | Remarks |
|---|---|---|---|---|---|---|
| **A** | 355 | 2.1 | 16 | 20 | **0.3** | Tube broken at **one** end |
| | 355 | 2.0 | 16 | 19 | **0.3** | Tube broken into **two** pieces |
| | 355 | 1.7 | 16 | 195 | **2.5** | Tube broken into **four** pieces |
| | 355 | 2.0 | 3 * | 1,790 | **23** | Tube smashed with a hammer in a polyethylene bag and transferred completely to the standardised 13-litre vessel |
| **B** | 480 | 1.8 | 3 * | 1,550 | **20** | |
| **C** | 310 | 1.0 | 3 * | 1,810 | **24** | |

* As the measurement range of the Hg monitor was possibly exceeded, measurement was discontinued after three hours.

### *7.1.1 Drop tests involving CCFL fluorescent tubes*

Despite all efforts to remove a total of 22 fluorescent tubes of various brands carefully from their metal receptacles, two of the tubes broke at the edge. The tests, in which the tubes, weighing two to three grams, were dropped onto a metal plate from a height of 1.20 m in order to break them, were frequently not successful and had to be repeated. Where tubes hit the metal plate on the ground parallel to their longitudinal axis, they generally broke into at least three parts. If they first hit the ground end-on perpendicular to the surface, it was even more difficult to bring about breakage, owing to the cut-off cable ends of the electrode and the silicone sealing mass at the end of the tube. In this form of the drop test, the tubes studied generally broke into two pieces.

### *7.1.2 Breakage of CCFL tubes in the 13-litre vessel*

The results in Table 4 show that the quantities of mercury vapour released from tubes that broke completely at only one point were relatively low over the course of the monitored period. The quantities of mercury emitted were greater when tubes broke into more than three parts or were destroyed completely. The mercury emissions from the CCFL tubes studied lay within a range between 0.3 and 20 µg of mercury per tube over test durations of between 2 and 16 hours. On the worst-case assumption that the maximum measured quantity of mercury vapour is distributed homogeneously within the test chamber (with a volume of 42 $m^3$) not over three hours, but within only 15 minutes, this would correspond to a concentration of 0.5 µg of mercury per $m^3$ within an unventilated room.

The mercury emission arising following a tube breakage is determined primarily by the number of fragments and by the form and distribution of the fragments on the ground. The dimensions (length, diameter) and mass of a fluorescent tube are clearly only secondary factors. The emissions measured permit the conclusion that the exposure in the event of breakage of a few CCFL tubes per shift will be below the OEL, even in a working area without mechanical ventilation.

## ***7.2 Release of mercury during the collection of CFLs and fluorescent tubes***

For simulation of the tasks of collection and storage of CFLs as they occur in the field, genuine collecting bins from a municipal waste disposal plant in Hesse were made available, together with end-of-life lamps. Brand-new plastic bins of identical design and with the same internal volumes of 60 and 150 litres were also used in the studies.

By repeated opening and closing of the collecting bins when almost full, it was first ascertained whether mercury vapour was in fact released and if so, on what scale. The tests were performed in the indoor area under summer and winter temperature conditions, since a higher proportion of emissions was to be anticipated at higher outdoor temperatures, assuming that lamp fragments were already present in the bins. In order to simulate further collection activities in the plant, a series of tests were performed in which end-of-life lamp material from the three bins was transferred in batches to empty new bins. These tests showed that each container already contained a small proportion of broken lamp material (1 to 2%), but also lamp types which were not to be collected and (unbroken) mercury thermometers. The transfer test also showed that a container rarely contained two CFLs of the same brand and type.

The range of lamps appeared to vary extremely widely from one bin to another; the mercury vapour concentration in the bins could therefore also be expected to differ widely. Under unfavourable conditions, such as poor ventilation in the room, the mercury concentration could rise, assuming peak values of up to several hundred µg of mercury per $m^3$ for a few seconds to several minutes, then falling again within a very short period, particularly when mechanical ventilation measures were switched on (**Tables 5** and **6**).

**Table 5:**
**Tests performed in a test chamber on 60-litre collecting bins filled with end-of-life CFLs**

<table>
<tr><th rowspan="2">Scenario/activity</th><th rowspan="2">Bin No.</th><th colspan="2">Mercury concentration* in $\mu g/m^3$</th><th colspan="2">Exposure peaks in $\mu g/m^3$</th></tr>
<tr><th>At bin rim (0.7 m height)</th><th>Within breathing range (1.5 m height)</th><th>Bin rim</th><th>Breathing range</th></tr>
<tr><td rowspan="3">Opening and closing the bin for 2 min in each case<br>*Sampling period 5 min in each case*</td><td>1</td><td>61</td><td>5</td><td rowspan="3">270 to 1,580</td><td rowspan="3">51 to 135</td></tr>
<tr><td>2</td><td>27</td><td>9</td></tr>
<tr><td>3</td><td>56</td><td>18</td></tr>
<tr><td rowspan="3">Transfer of three 2.5 kg lamps into an empty bin; duration 10 min in each case; then closure of bin<br>*Sampling period 120 min in each case*</td><td>1</td><td>9.6**</td><td>6.8**</td><td rowspan="3">125 to 535</td><td rowspan="3">25 to 145</td></tr>
<tr><td>2</td><td>3.4**</td><td>2.7**</td></tr>
<tr><td>3</td><td>4.4**</td><td>2.4**</td></tr>
<tr><td colspan="2" rowspan="6">Breakage of lamps of same type without outer case from six manufacturers in empty bin;<br>*** opened twice for 2 min within 15 min<br>*Sampling period 15 min in each case*</td><td>16</td><td>1</td><td rowspan="6">70 to 960</td><td rowspan="6">10 to 152</td></tr>
<tr><td>41</td><td>6</td></tr>
<tr><td>82</td><td>16</td></tr>
<tr><td>46</td><td>4</td></tr>
<tr><td>- -</td><td>4</td></tr>
<tr><td>- -</td><td>7</td></tr>
</table>

Detection limits: a) IFA's standard measurement method with 2 h sampling: ≤ 0.2 $\mu g/m^3$ Hg
b) Direct-reading measurement method: ≤ 2 $\mu g/m^3$ Hg

* Measurement readings of direct-reading measurement instruments as mean values over the sampling period

** Results of IFA's standard measurement method for mercury, IFA work folder, code 8530

*** In most cases, the lamps' helical glass tubes broke into two or three individual pieces and a remainder of small fragments. If the lamp was still intact after hitting the bottom of the bin, it was smashed by striking it with a metal rod.

**Table 6:**
**Tests performed in a test chamber in a 150-litre collecting bin containing end-of-life fluorescent tubes, length 1 m, 38 W**

| **Scenario/activity** | **Mercury concentration * in µg/m³** | | **Exposure peaks in µg/m³** | |
|---|---|---|---|---|
| | **At bin rim** (1.0 m height) | **Within breathing range** (1.5 m height) | **Bin rim** | **Breathing range** |
| Smashing of three fluorescent tubes of the same manufacturer in the empty bin at intervals of 2 min within sampling period*; ** air change λ = 1 | 34 | 4 | up to 450 | up to 61 |
| Bin opened and closed twice within sampling period*; air change λ = 1 | 83 | 66 | up to 1,037 | up to 677 |
| Mechanical ventilation of open bin during sampling period*; air change λ = 15 | 214 | 71 | up to 1,730 | up to 890 |

* Measurement readings of direct-reading measurement instruments as mean values over the sampling period of 15 min

** When struck with a metal rod in the bin, the fluorescent tubes broke in most cases into two or three larger pieces.

### *7.3 Release of mercury following the breakage of CFLs and fluorescent tubes on the ground*

By means of tests performed in the test chamber, scenarios were also simulated based upon studies by the German UBA and the Bavarian LGL [6 to 8; 19; 20]. Mercury exposure levels were determined that could arise when for example a CFL or a fluorescent tube falls on the ground whilst being changed and breaks, as in the domestic scenario upon which the recommendations of the German UBA are based.

For this purpose, breakage tests involving a number of brands of lamp were performed on the floor of the test chamber in a metal trough (0.8 m × 1.0 m × 0.1 m) lined with film, with the mechanical ventilation switched off.

To facilitate comparison of the maximum mercury concentration during the release and dissipation of mercury vapour in the room, the lamps in the trough were broken at the mid-point. The results are shown in **Tables 7** and **8**.

Mercury above the detection limit was not measured in the breakage tests involving brand-new CFLs that had not yet been operated electrically. When brand-new CFLs were broken whilst still in the hot state (with a surface temperature of approximately 50 to 60 °C) immediately after being switched off after several hours in use, exposure levels occurred which were somewhat lower than those arising in the breakage tests involving cold end-of-life lamps.

**Figure 5** shows that when burnt-out and disposed-of end-of-life lamps break, high peaks occur briefly, followed by somewhat lower peaks whilst the fragments are being swept up; the values then drop immediately as a result of ventilation.

**Table 7:**
**Tests performed in a test chamber of the mercury emission immediately following the breakage of end-of-life and brand-new CFLs in a floor trough**

| **Scenario** | **Mercury concentration* in µg/m³** | | **Exposure peaks in µg/m³** | |
|---|---|---|---|---|
| | **At trough rim** (0.1 m height) | **Within breath-ing range**** (0.7 m height) | **Trough rim** | **Breathing range** |
| **1. End-of-life (faulty) CFLs** (from collection by waste disposer in 2011 and 2012) | | | | |
| Breakage of lamps of manufacturers 1 to 5 | 7<br>8<br>13<br>- -<br>- - | 5<br>7<br>12<br>4<br>< 2 | 92 to 186 | 2 to 115 |
| **2. Brand-new CFLs** (purchased in September 2012) | | | | |
| Breakage of cold lamps of<br>manufacturer 6<br>manufacturer 7 | <br>- -<br>- - | <br>< 2<br>< 2 | <br>---<br>--- | to 2 |
| Breakage of hot lamps (lamp surface temperature: 50 to 60°C) of<br>manufacturer 6<br>manufacturer 7<br>*(Lamp operation one hour)* | <br><br>- -<br>- -. | <br><br>3<br>3 | <br><br>---<br>--- | 14 to 35 |
| Breakage of hot lamps (lamp surface temperature: 50 to 60°C) of<br>manufacturer 6<br>manufacturer 7<br>*(Lamp operation one week, switched on/off ten times per day)* | <br><br>- -<br>- - | <br><br>2<br>3 | <br><br>---<br>--- | <br><br>3 to 31<br>18 to 62 |

* Measurement readings of direct-reading measurement instruments as mean values over the sampling period of 15 min
** A height of 0.7 m is assumed to be the inhalation range of a bending or crouching adult or of children standing upright when sweeping up the lamp fragments

**Table 8:**
**Tests performed in a test chamber of the mercury emission immediately following the breakage of end-of-lief and brand-new fluorescent tubes in the floor trough**

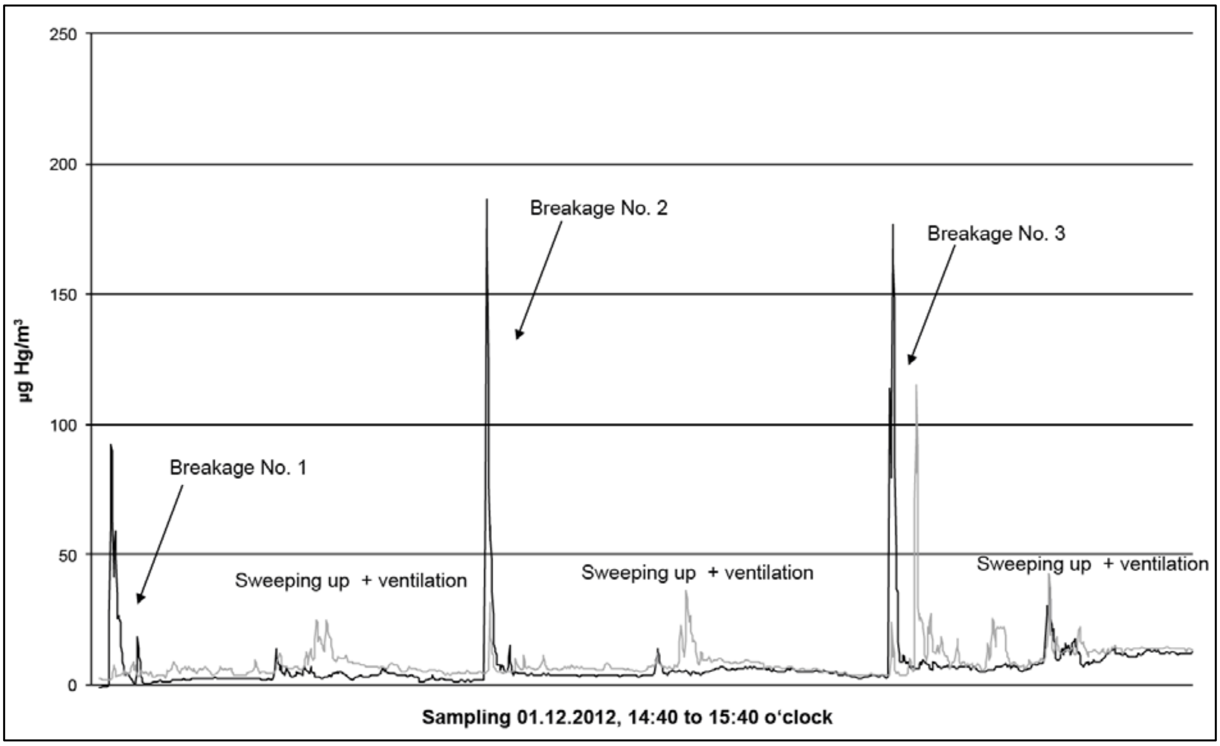
| **Scenario** | **Mercury concentration* in $\mu g/m^3$** | | **Exposure peaks in $\mu g/m^3$** | |
|---|---|---|---|---|
| | **At trough rim** (0.1 m height) | **Within breath-ing range**** (0.7 m height) | **Trough rim** | **Breathing range** |
| **1. End-of-life (faulty) fluorescent tubes** (from collection by waste disposer in 2011 and 2012) | | | | |
| Breakage of fluorescent tubes in 2011<br>Manufacturers 1 to 3<br>18 to 20 W<br>Length: 0.58 m | 11<br>7<br>21 | 13<br>8<br>66 | 105 to 1,460 | 31 to 175 |
| Breakage of fluorescent tubes in 2012<br>Manufacturers 4 to 10<br><br>36 to 58 W<br>Length 1.0 to 1.5m | -- | 9<br>37<br>25<br>49<br>3***<br>3***<br>6*** | | 6 to 270 |
| **2. Brand-new fluorescent tubes** (from the retail trade in 2012, manufacturer 1) | | | | |
| Breakage of new fluorescent tubes,<br>38 W, length 1 m | - - | 6 | | Up to 45 |

* Measurement readings of direct-reading measurement instruments as mean values over the sampling period of 15 min

** A height of 0.7 m is assumed to be the inhalation range of a bending or crouching adult or of children standing upright when sweeping up the lamp fragments

*** When these end-of-life fluorescent tubes broke, there was no typical implosion due to the lack of vacuum, so it is assumed that the fluorescent tubes' mercury had already leaked out.

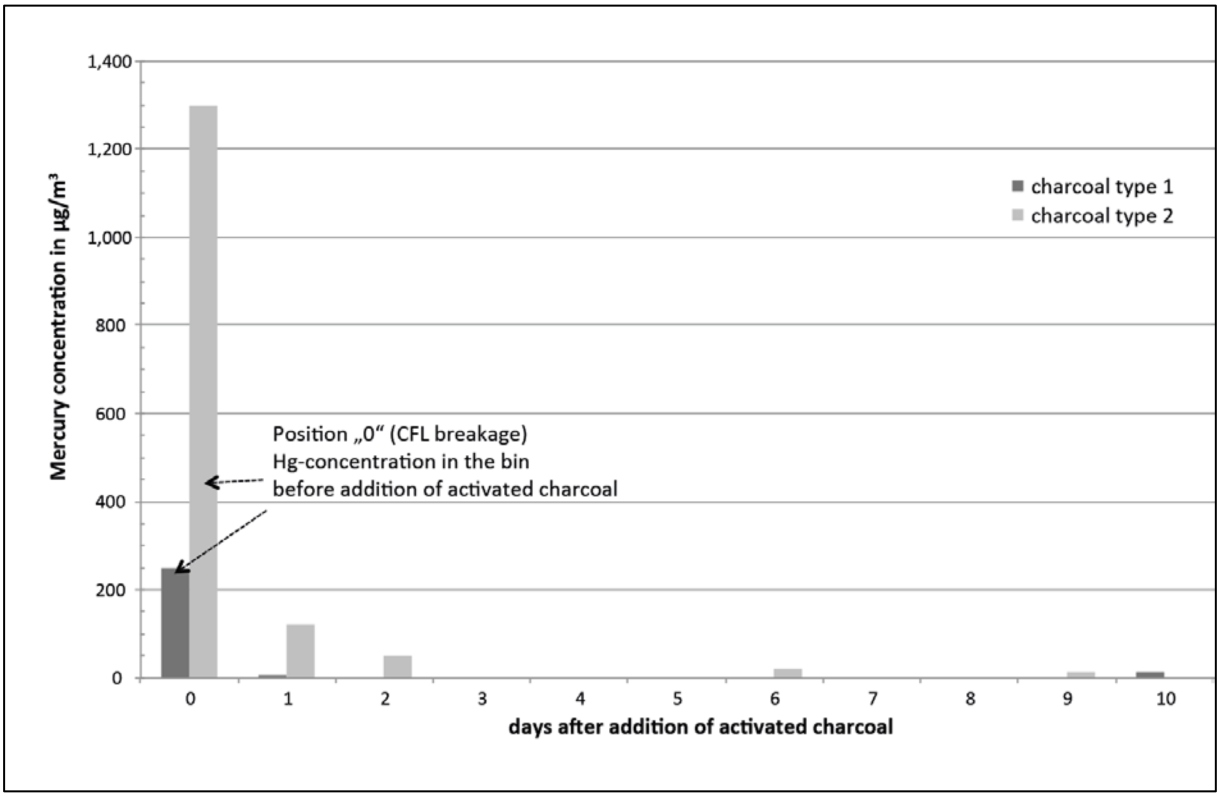
**Figure 5:**
**Breakage of three CFLs in a floor trough with sweeping up and ventilation (15-fold air exchange);**
black line: trough rim at a height of 0.1 m, grey line: at a height of 0.7 m above the trough




## *7.4 Technical protective measures*

In the tests performed in the test chamber, measures were also studied for reduction of the exposure to mercury, for example when the collecting bins are opened. Mechanical measures for reducing the exposure were tested in the form of two different fume collection facilities. A further measure was the adsorption of mercury vapours by the insertion of activated charcoal in batches into the bins. The activated charcoal types considered are able to bind mercury vapours by virtue of impregnation with iodine or sulphur compounds during their manufacture. The insertion of 100 g of activated charcoal into a 60-litre plastic bin filled with broken lamp material resulted in a reduction in mercury vapour concentration of over 80% within 24 hours (**Figure 6**).

**Figure 6:**
**Reduction in the mercury concentration by the insertion of 100 g of activated charcoal into a 60-litre collecting bin containing seven broken CFLs**




Mechanical ventilation measures involving ring or baffle collection elements (**Figures 7** and **8**) above the collecting bin route the mercury vapour released from the bin immediately away at a discharge rate of 400 m³ per hour and an intake velocity of 10 m/s. The effectiveness of vapour collection is considerably impaired by a crossflow with a velocity exceeding 0.5 m/s in the vicinity of the collection elements.

**Figure 7:**
**Collection by means of a ring**

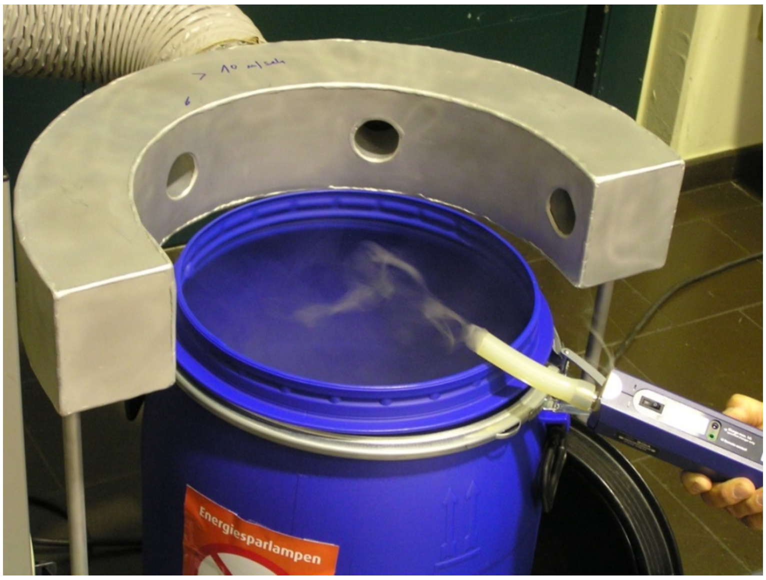
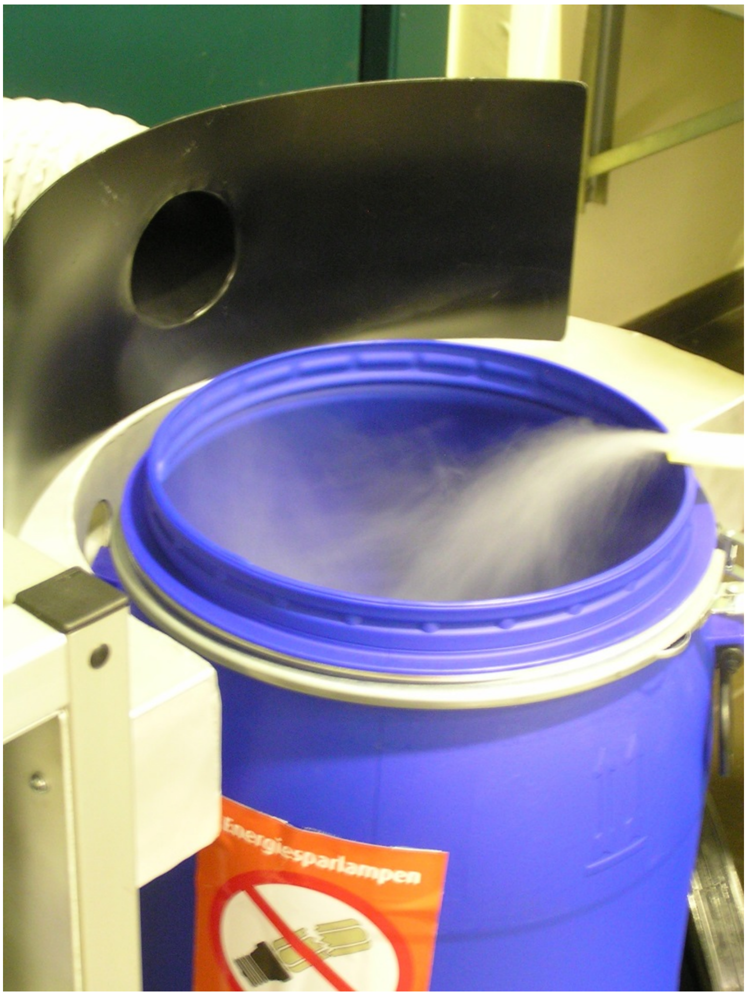


**Figure 8:**
**Collection by means of a baffle**




### *7.5 Conclusion*

If the results of the tests performed in the test chamber are considered over the duration of a shift and these concentrations are compared to the OELs currently in force, the mean shift value and the short-time value for mercury are seen to be observed. The tests involving activated charcoal demonstrate impressively how the mercury vapour concentration within the bin can be reduced. The tested alternatives for collection show the ways of reducing the release of mercury at the workplace when collection is performed in indoor areas.

## 8 Measurement campaign of the accident insurance institutions

The working group has decided to conduct a measurement campaign in order to determine the inhalation exposure to mercury systematically in the following working areas:

- Manufacture of lamps, including electronic signage, containing mercury
- Collection of end-of-life lamps

- Recycling of lamps containing mercury, including cold-cathode lamps found in flat screens and monitors

A guidance document for the measurement strategy and for documentation was drawn up for this purpose. Standard sampling is performed in accordance with IFA measuring method 8530 by means of personal air samplers on a glass cartridge with two hopcalite phases each of 1.0 g, separated by quartz-fibre filters. Mercury is analysed on the prepared hopcalite phases by means of atomic fluorescence spectroscopy at 253.7 nm. At a sampling duration of two hours, a detection limit of 0.20 µg/m³ is attained [18]. Direct-reading sampling is also possible by means of mercury vapour monitors.

Pilot measurements have already been performed at collection points and during the recycling of flat-screen TVs and monitors.

## 9 Future prospects

The MGU measurement campaign for exposure assessment is being conducted by the German Social Accident Insurance Institutions in conjunction with the IFA from July 2012 to June 2015 in the working areas referred to above.

The Federal Institute for Occupational Safety and Health (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, BAuA) and the State Institute for Environmental Protection of Baden-Württemberg (Landesanstalt für Umwelt, Messungen und Naturschutz Baden Württemberg, LUBW) intend to determine mercury exposure at waste collection points in co-operation with the individual statutory accident insurance institutions. The BAuA is also planning to conduct biomonitoring.

At the end of the measurement campaign, the results will be presented in a further publication. Based upon the results, protective measures by which exposure can be minimized are to be described in a sector-specific DGUV informative publication.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