Commission guidance on abatement technologies for emissions of mercury from crematoria

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Acronyms

BAT: Best Available Technique

ERV: Emergency Release Vent

HELCOM: Baltic Marine Environment Protection Commission (“Helsinki Commission”)

Hg: Mercury

Hg (0): Elemental mercury

Hg (II): Oxidised mercury

Hg (P): Particle-bound mercury

OSPAR: Mechanism by which 15 Governments and the European Union cooperate to protect the marine environment of the North-East Atlantic (originating from originally “Oslo and Paris Conventions”)

PCDD/F: Dioxins and furans

PCS: Process Control System

PLC: Programmable Control Logic

PM: Particulate matter

SPC: Sorbent Polymer Composite

TOC: Total organic compounds

VOC: Volatile organic compounds

1. Introduction

The objective of this guidance is to support Member States with applying abatement techniques for emissions of mercury and mercury compounds from crematoria. This guidance covers determining best available techniques (BAT), BAT-associated emissions and environmental performance levels, cost data and permit conditions based on BAT. While recommendations on BAT for mercury emissions from crematoria exist in OSPAR and HELCOM, a limited number of Member States are signatories and there is no EU-level legislation covering installations of mercury abatement techniques in crematoria. As such, this guidance is intended to support Member States implementing controls at national, regional or local level, and be of particular use to those Member States which do not currently have legislation regulating mercury emissions from crematoria. Installing mercury reduction techniques based on activated carbon leads to significant co-benefits by also reducing emissions of organic pollutants like dioxins and furans.

This guidance contains the following sections:

- **Section 2:** Sector overview including summary of cremation processes and mercury emissions in the EU.
- **Section 3:** Best available techniques for mercury abatement in crematoria.
- **Section 4:** Summary of existing Member State legislation.
- **Section 5:** Guidance on mercury emissions monitoring practices, techniques and standards in crematoria.

1.1. Policy Context

The EU has implemented a number of relevant policies with the aim of controlling, eliminating and, where this is not feasible, reducing use and exposure to mercury. The most recent is Regulation (EU) 2017/852 on mercury, and amended Regulation (EU) 2024/1849, which addresses the whole life cycle of mercury from primary mining to its final disposal as waste. It mainly implements the Minamata Convention[1], but also collates and strengthens mercury-related measures from earlier European acts and further develops the legal framework in areas such as dental amalgam, use of mercury in products and processes and waste disposal.

Whilst the revision of the Mercury Regulation includes the phase out of the use of dental amalgam and banning the manufacture and export of certain products, no legally-binding

[1] Minamata Convention on Mercury – Text and Annexes, United Nations Environment Programme, Geneva, 2024 https://minamataconvention.org

amendments (directly) tackling mercury emissions from crematoria were made. As a result, the revision retained the development of a non-legally binding guidance document setting out what should be considered as BAT for the control of mercury emissions from crematoria. Member States will be obliged to provide information on the implementation of the guidance in Article 18 reporting under the Mercury Regulation. Finally, the Commission shall report by 31 December 2029 on the implementation and impact of the guidance applied in Member States.

1.2. Development of this guidance document

A literature review was conducted into:

1. information in relation to processes used in crematoria, including description of the different technical elements of a crematorium, and different types of crematoria. Key sources reviewed include VDI Guidelines 3891[2] and academic articles including Schetter and Bittig (2020)[3]. One interview was also conducted with an electric crematorium provider, to supplement the relative lack of information on this type of crematorium. Information has been summarised in Section 2.2.
2. the origin and fate of mercury during cremation. Key sources reviewed include Ohle et al. (2021)[4] and Takaoka et al. (2021).[5] Findings are presented in Appendix 1.
3. mercury abatement techniques, their applicability limitations, environmental performance, and different types of costs.

This was supplemented with interviews with technique providers, who were asked a range of questions relating to mercury abatement techniques in crematoria, in relation to technique applicability, performance and cost, as well as broader market questions such as countries where techniques are installed/operated.

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[2] VDI-Richtlinie 3891:2024 Emission control - Human cremation facilities, Final draft, VDI e.V., Düsseldorf, September 2024

[3] Schetter, G.; Bittig, M.: Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen (Environmental relevance and State of the art in Cremation facilities). Umweltbundesamt (Ed.), Texte 26, Dessau-Roßlau, 2020 https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-02-03_texte_26-2020_einaescherungsanlagen.pdf

[4] Ohle A. et al. (2021) Quecksilber- und Feinstaubemissionen von Krematorien: Ein Überblick. Chem. Ing. Tech. 93, No. 3, p. 390–411 https://doi.org/10.1002/cite.202000122

[5] Takaoka M. et al. (2021) Mercury removal from the flue gases of crematoria via pre-injection of lime and activated carbon into a fabric filter. Process Safety Environ. Protect. 148, 323-332 https://doi.org/10.1016/j.psep.2020.10.027

2. Sector overview

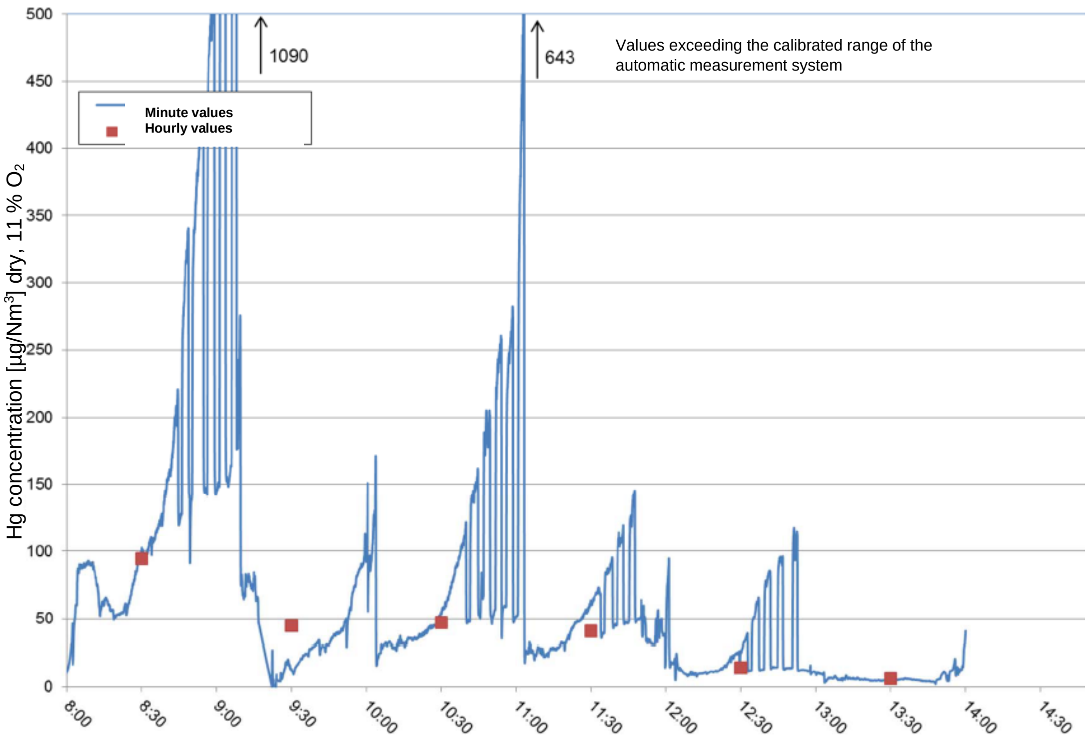
2.1. Introduction

Mercury and its compounds present a significant risk to both the environment and human health due to their toxicity. While mercury occurs naturally, the high concentrations found in the environment are primarily the result of human activities. Mercury contamination in environmental media—such as water, soil, sediment, and living organisms—poses a serious health threat, particularly to unborn babies and infants, who are especially vulnerable to irreversible damage to the central nervous system if exposed to excessive amounts[6].

The main source of mercury in crematoria is the human body, more specifically dental amalgam fillings. During the combustion of the coffin in the main combustion chamber of a crematorium oven, mercury is completely volatized in elemental form. The release occurs within some minutes causing a short, but steep spike in mercury concentration in the combustion gas (see Figure 2-1), also associated with variations of volume flow and oxygen content. This is challenging for mercury abatement systems as well as for measurements (referring to standard conditions and reference oxygen content). Depending on the temperature and the concentration of reactive gases such as chlorine, sulphur species, nitrogen oxides, and dust, elemental mercury (Hg^0) may be oxidized to Hg^{2+}. All forms of mercury may be partially bound at the surface of dust particles. Therefore, in the flue gas, mercury may occur in gaseous elemental form Hg^0, gaseous oxidized form (Hg^{2+}), or particle bound (Hg^P).

[6] WHO (2021) Preventing disease through healthy environments. Exposure to mercury: a major public Health concern. 2nd Edition, World Health Organisation, Geneva/Switzerland https://www.who.int/publications/i/item/9789240023567

Figure 2-1: Typical variation of mercury emissions from six cremations



Source: Bittig/Haep (2018)[7]

Mercury may leave crematoria via several pathways. In the absence of dedicated pollution control, mercury will be emitted as part of the flue gas. Once it has left the stack it will be highly dispersed and undergo long-range transport and later dry or wet deposition. Mercury may be cycled in the atmosphere so that any local emissions may lead to deposition far from the original source.

Another part of mercury may be bound in dust or activated carbon collected in filters. Such material needs to be managed properly to avoid secondary emissions and releases. In certain cases where the flue gas cools down too much, mercury may condensate within the stack and contaminate construction materials. Ashes for burial, on the other hand are typically very low in mercury. More information about the emission paths of mercury may be found in chapter 6.3 in the appendix.

[7] Bittig, M.; Haep, S.: Quecksilberemissionen aus Krematorien – Welchen Herausforderungen muss sich die Abgasreinigung stellen? In: Krematorien - Quecksilber und andere Umwelteinflüsse, Fachverlag des deutschen Bestattungsgewerbes, Düsseldorf, 2018

2.2. Summary of cremation processes

This section provides a description of the main technical elements of a crematorium, in particular those parts that are relevant to the emission of mercury. The almost 150-years history of crematoria in Europe has produced various types of design, which differ, for example, in the type and arrangement of the combustion chambers, the heat energy supply and the flue gas treatment systems. New developments and trends, e.g. the use of aqueous/alkaline processes as well as the changing prevalence of electrical energy instead of fossil fuels is also described and compared with the techniques currently prevailing.

A cremation facility according to guidance document VDI 3891[8] consists of several individual components. Each component and any variations in different configurations of crematoria are detailed within this section and include the following:

- coffin insertion machine/entry device
- cremator/cremation oven consisting of a main combustion chamber, a post combustion chamber and, possibly a separate ash burnout chamber/zone
- flue gas cooling system with/without heat recovery
- flue gas cleaning/purification system
- exhaust gas discharge system including stack
- bypass
- process control system including safety concept
- emission monitoring systems
- ash processing unit/discharge
- residue disposal/dust discharge
- peripheral equipment

2.2.1. Coffin insertion machine

The coffin containing the deceased is placed into the primary chamber (see 2.2.2) through a doorway. In case of a hot start cremator a coffin insertion machine is necessary (see VDI 3891)[8]. The coffin insertion machine is normally stationary and may be referred to as the charging system. Loading may be manual or partly automated and must be supervised by operating personnel. The system must be interlocked with the cremator control system to prevent flame flashback or the release of fugitive emissions into the loading room.

[8] VDI-Richtlinie 3891:2015 Emission control - Human cremation facilities. VDI e.V., Düsseldorf, 2015

Specifically in the case of flat-bed cremators, in some crematoria the coffin insertion machine can automatically transfer ash to the ash burnout chamber.

2.2.2. Cremator

There are two main types of cremators, with either a **multi-stage cremator** or a **flat-bed cremator.** Multi-stage cremators use several floors arranged one above the other (for cremation, ash burnout and subsequent ash removal) allowing ash removal by gravity and are typically used for higher capacity/throughput crematoria i.e. with a higher number of cremations per year[12]. In flat-bed cremators, the coffin remains on a closed floor and ash is transferred to the ash burnout chamber either with an automated rake or with a manual tool[12].

Most installations are heated by using natural gas as an energy source, some use other gaseous or liquid fuel such as biogas, hydrogen, liquified natural gas (LNG) or oil[2]. Electric energy is also used as an energy source in some cases. According to an interview with one provider, electric crematoria were in decline in Europe, however there is increasing interest and the potential for increased uptake in consideration of wider environmental objectives around clean energy and reduction in fossil fuel use. Cremators can be cold start or warm start, depending on the number of cremations undertaken in a year. Typically, cold start cremators are used in smaller capacity crematoria performing maximum 750 cremations per year and hot start in larger crematoria performing 750 cremations or more per year[9]. Cold start cremators start with a cold (ambient air) primary cremation chamber for the first cremation of the day, the primary chamber is then cooled between subsequent cremations[9]. Typically coffin insertion is manual and therefore cooling is needed to safely allow for coffin insertion. Hot start cremators on the other hand begin with a pre-heated primary chamber with automatic insertion of the coffin and are able to perform more cremations in a working day than the cold start[9].

Regardless of the oven type, the combustion process takes place in a primary (“main combustion”) chamber where the coffin is burned, and a secondary (“post combustion”) chamber aiming at the complete combustion of organic compounds in the waste gas[10]. Both primary and secondary chambers have a refractory lining to retain heat and protect temperature sensitive equipment[11]. A basic high-level schematic of a crematorium is shown in Figure 2-2.

[9] DFW Europe, 2024, FAQ Cremation Frequently Asked Questions Cremations. https://dfweurope.com/faq/#:~:text=Cold%20start%20cremators%20are%20a%20good%20investment%20for%20crematories

[10] Schetter, G.; Bittig, M.: Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen (Environmental relevance and State of the art in Cremation facilities), Umweltbundesamt (Ed.), Texte 26, 2020

[11] DEFRA, Environmental permitting technical guidance PG5/2(23), 2021

The **primary ("main combustion") chamber** provides sufficient temperature and oxygen for the initiation of the coffin combustion. During the subsequent **ash burnout,** the mineralisation of the ash is completed (conversion of black ash into white ash)[12]. The **secondary ("post combustion") chamber** has to provide sufficient temperature, oxygen and residence time for the destruction of organic compounds[12].

Some countries regulate the minimum temperature to ensure the destruction of organic compounds. Sweden and Finland set a minimum limit of 700 °C and 750 °C respectively. Some countries additionally set both a minimum and a maximum temperature for coffin introduction: France (350 °C – 900 °C), Italy (300 °C – 800 °C) and Belgium (Wallonia) (700 °C – 900 °C). More countries set a minimum temperature for the secondary chamber, the range of which is much narrower with the limit set at 800 °C or 850 °C in all countries[13]. Similarly, 850°C is the minimum combustion temperature required for waste incineration and waste co-incineration in Europe[14]. However, to reduce energy costs and greenhouse gas emissions, an increasing number of crematoria have applied for exemptions using slightly lower temperatures (e.g. 750°C) as there is growing evidence that no increase of PCDD/F emissions is associated.[15] Finland has also commented that while minimum temperature requirements of 750 °C promote clean burning, it is also the case that there are situations where cremation must be started at lower temperatures, for example coffins with weight over 300kg. In this scenario, the burning of fat may overwhelm the chamber and lead to temperatures rising to >1300 °C which can be damaging to masonry.

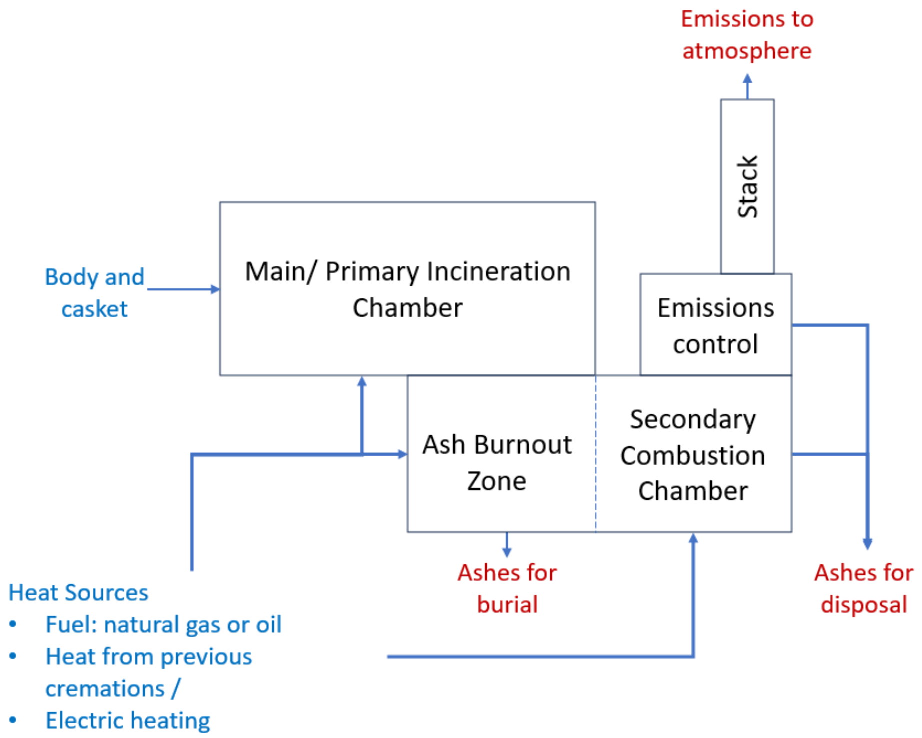
[12] VDI-Richtlinie 3891:2015 Emission control - Human cremation facilities. VDI e.V., Düsseldorf, 2015

[13] ECN- Chart comparing atmospheric emissions of crematoria - ind 2 - COMPLET-V2.xlsx (dfweurope.com)

[14] Industrial Emissions Directive 2010/75/EU, amended by Directive (EU) 2024/1785 of 24 April 2024

[15] Schetter, G.: Langzeituntersuchungen zu Emissions- und Schadstoffminderungen in Krematorien durch veränderte energieeffiziente Betriebsweisen. Deutsche Bundesstiftung Umwelt (Ed.), 2016 https://opac.dbu.de/ab/DBU-Abschlussbericht-AZ-31407.pdf

Figure 2-2: High level schematic of a cremation facility



Source: Sircar (2002) [16]

The primary combustion chamber of a **flat-bed cremator** has a solid hearth where cremation as well as the ash burnout take place. Some flatbed cremators are equipped with an additional ash burnout chamber. The main chamber of a **multi-stage cremator** is equipped with coffin support brackets and another unit below the primary chamber for separate ash burnout[17]. More detail in the different aspects of flat-bed and multi-stage cremators is outlined below.

Operational control measures such as ensuring the air tightness of the combustion chamber and the castings as well as negative pressure when opening the door for coffin introduction will minimise the release of combustion gases including reducing mercury release alongside other harmful emissions[18]. For gas and oil cremators, usually a single burner is installed to

[16] Sircar, R.: Untersuchung der Emissionen aus Einäscherungsanlagen und der Einsatzmöglichkeiten von Barrierenentladungen zur Verringerung des PCDD/F-Austrages, Dissertation, Universität Halle-Wittenberg, 2002 https://opendata.uni-halle.de/bitstream/1981185920/9884/1/prom.pdf

[17] Schetter, G.; Bittig, M.: Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen (Environmental relevance and state of the art in cremation facilities), Umweltbundesamt (Ed.), Texte 26, 2020

[18] Guidelines on best available techniques and provisional guidance on best environmental practices, Section VI.G Guidance/guidelines by source category: Source categories in Part III of Annex C, Part III source category (g): Crematoria, Stockholm Convention, 2007

maintain temperature of the secondary chamber although more than one burner may be used[17]. For electric cremators, electric heating elements are used. In both cases, retained heat from the primary chamber is usually sufficient to achieve the required minimum temperature in the secondary chamber[17]. Supplementary air may be added to ensure sufficient oxygen for complete combustion. For warm start cycles, the primary chamber is preheated using heat from the previous cremation in the secondary combustion chamber, whereas the secondary chamber is preheated by the fuel source[17].

There are five phases of the batch combustion process excluding pre-heating and shut down of the cremator. The time of a cremation to complete varies significantly depending on multiple factors, such as body size/weight and temperature of the primary chamber. During the combustion all substances are incinerated and vaporised excluding non-combustible material and some bone fragments[19].

The phases of combustion and indicative timings are presented below:

- Brief flash 'volatilisation' of the veneer on the outside of the coffin (1 min)
- Coffin combustion (20 min)
- Break open of the coffin and final combustion of the coffin and cremation of the body (40 mins)
- Calcination of the remains (30 mins)
- Ashing (2 mins)

Following combustion, unburnt remains (ash, bones, non-consumed metal objects such as screws, nails, and other parts of the coffin or container, dental remains, dental gold, surgical screws, prosthesis, implants) are collected in an ash pan or tray in the primary chamber (flat-bed cremator) or a separate ash burnout chamber (multi-stage cremator)[20]. The remains are then processed (see section 2.2.8).

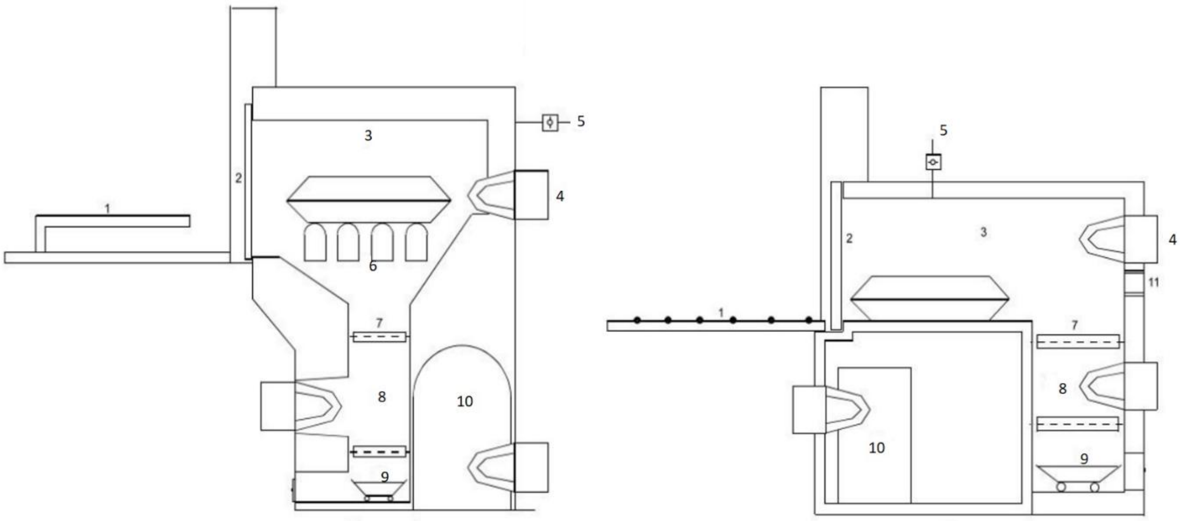
Figure 2-3 shows the different layout of multi-stage cremator and flat-bed cremator, which are outlined in detail below.

http://chm.pops.int/Portals/0/Repository/batbep_guideline08/UNEP-POPS-BATBEP-GUIDE-08-12.English.PDF

[19] EMP/EEA emission inventory guidebook, NFR 6.C.d. Cremation, European Environment Agency, Copenhagen, 2009

[20] EMEP/EEA emission inventory guidebook, 5.C.1.b.v Cremation, European Environment Agency, Copenhagen, 2013

Figure 2-3: Process scheme of multi-stage cremator (Left) and flat-bed cremator (Right)



(1) Coffin insertion machine, (2) Oven door, (3) Primary combustion chamber, (4) Burner, (5) Combustion air supply, (6) Supporting bricks for coffin, (7) turntable, (8) Ash burnout chamber, (9) Ash collection for disposal, (10) Secondary or post combustion chamber, (11) Scraper for ash disposal

Source: Sircar (2002) [16]

2.2.2.1. Multi-stage cremator

The defining characteristic feature of multi-stage cremator systems is that ash transportation occurs by gravity via chambers locked by rotating plates one above each other[8]. They utilise several floors arranged one above the other for cremation, ash burnout and removal. The coffin rests on supporting bricks over two or more heat-resistant rotating plates[3]. The area between the rotating plates forms the burn-out zone. During the cremation process, the ash produced falls onto the upper rotating plate. Upon completion of cremation, this rotates so that ash falls to the plate below[10]. The ashes are transported to the ash burnout chamber in this way gradually at set intervals (usually of around 1 hour[2]), and after an additional interval (1 hour) the burned-out ash is transferred to the ash cooling chamber. Metal parts as well as prosthetics and implants are removed before the ash is pulverized using a so-called cremulator. The resulting powder is then transferred into an urn[11].

Combustion begins in the primary (main) combustion chamber once the oven door is closed. If required to maintain temperature a single burner typically fuelled by natural gas or liquified petroleum gas can be used [3,21]. Certain crematoria also have more than one burner in a range of configurations. The direction of flame can be controlled to a limited extent by

[21] DFW Europe, FAQ Cremation Frequently Asked Questions Cremations, 2024 https://dfweurope.com/faq/#:~:text=Cold%20start%20cremators%20are%20a%20good%20investment%20for%20crematories

adjusting the injection of combustion air[19]. Flue gas from the main chamber enters the secondary (post) combustion chamber and is oxidised due to the addition of secondary air. A burner is used within the secondary combustion chamber to ensure compliance with the required minimum temperature in the post combustion zone[2].

Due to the zonal structure of multi-stage cremators, the main combustion chamber can be refilled after each rotation of the upper plate. Appropriate measures to ensure ashes from individual cremations are kept separate such as rotary grates or flaps, must be installed in the primary combustion chamber[22]. The ashes are thermally treated using an additional burner, for the duration of the cremation process[3]. Ash processing is discussed further in section 2.2.8.

2.2.2.2. Flat-bed cremator

Flat-bed cremators are characterised by the use of a closed bottom ("hearth") as a coffin support surface[8]. The ash residues are removed by means of a slider of the burnout zone. Two rotating plates are used to limit the burnout zone as in the case of multi-stage cremators. Flat-bed cremator systems can be installed over $1^1/_2$ to 2 stories ("heavy" systems) or on the same level ("medium-heavy" systems)[3]. Additionally, smaller less frequently used flat-bed crematoria may have the ash burnout zone integrated into the main combustion chamber; however, this layout is not well suited to conducting a large number of cremations per day[12].

Both flat-bed and multi-stage cremator systems differ in burner technology and design of the post combustion chamber[3]. However, the thermal conditions and combustion process are identical in both cremator systems[3,2].

2.2.2.3. Electric crematoria

Electric cremators use several electrical heating elements (often there are 6 in total) housed in the walls of the furnace (Figure 2-4), which indirectly heat the primary chamber to above auto-ignition temperature. During the cremation, no additional energy/ heat can be added, however air must be provided to sustain combustion[22]. These systems require permits to allow these cremator systems to operate at lower minimum temperatures in the post combustion chamber [3].

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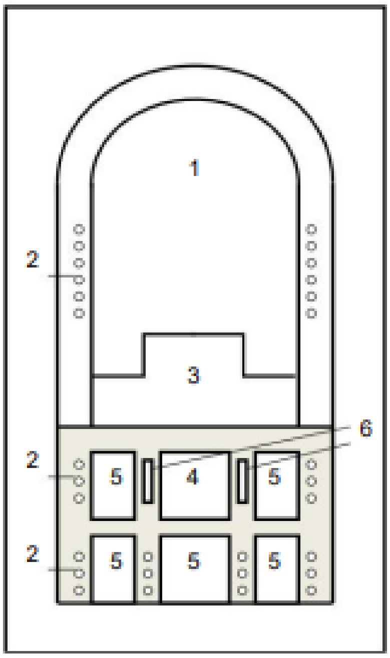
[22] DEFRA, Environmental permitting technical guidance PG5/2(23), 2014 https://www.gov.uk/government/collections/technical-guidance-for-regulated-industry-sectors-environmental-permitting

Figure 2-4: Electric oven schematic



(1) Main combustion chamber, (2) Electric heating, (3) coffin support grid, (4) Ash burnout channel, (5) Post combustion channel, (6) Air supply.

Source: Schetter/Djeradi (2013) [23]

While in gas-fired crematoria, combustion of the fuel source creates more flue gas including water vapour, CO_2, and CO which is mixed with the combustion of the cremation itself, in the case of electric crematoria, there is only the combustion of the cremation. As such, the volume of gas is about 30% lower. Additionally, required energy inputs are lower (e.g. for 1500 cremations per year it is ~25 kW per cremation, equivalent to 2.5 m^3 natural gas compared to ~25 m^3 for a multi-stage cremator and ~50 m^3 for a flat-bed cremator according to one electric oven provider).

2.2.3. Flue gas cooling system with/without heat recovery

At the outlet of the cremator, flue gas temperatures are normally higher than 700 °C. On the other hand, with respect to the use of fabric filters and carbon-based sorbents for gas cleaning flue gas should not exceed a limit depending on the quality of the sorbent material (e.g. 150 °C in some cases). Flue gas cooling can be achieved either by injection of cooling water into the flue gas (direct cooling) or by using a gas-water heat exchanger (indirect cooling).

[23] Schetter, G., Djeradi, B.: Handbuch für bayerische Krematorien, ISBN 978-3-936057-38-6, FVB Verlag, Düsseldorf, 2013

2.2.3.1. Direct flue gas cooling systems

Direct flue gas cooling of flue gases can be achieved by injection of water ("evaporation cooling") which is faster than indirect cooling systems[2]. Evaporation cooling involves the injection of a liquid (usually water) into the hot flue gas, causing shock-cooling and evaporation of the flue gas[24]. The fast process of direct cooling minimizes the generation of PCCD/PCDF[2].

The advantage of more rapid direct cooling is offset by an increased flue gas volume, which requires greater dimensioning of the flue gas cleaning system (e.g. filter and fan[2]. The addition of water is also associated with increased corrosion of all subsequent components, mainly caused by the formation of sulfuric acid (H_2SO_4) and sulphurous acid (H_2SO_3). Under certain weather conditions, the increased humidity results in a plume of visible water vapour which is potentially misinterpreted as pollution. Finally, the injection of water prevents heat utilisation[5].

Figure 2-5: Direct cooling system with water injection

Source: Schetter/Djeradi (2013) [23]

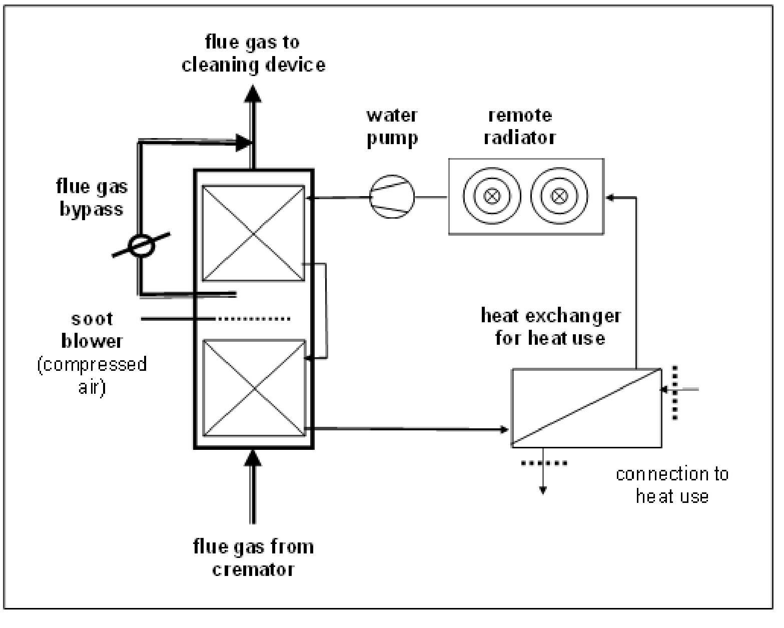
[24] Schetter, G.; Bittig, M.: Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen (Environmental relevance and State of the art in Cremation facilities), Umweltbundesamt (Ed.), Dessau-Roßlau, 2020

2.2.3.2. Indirect flue gas cooling systems

Indirect cooling takes place in heat exchange systems integrated into a closed circuit. There are two types of heat exchange systems: gas/air and gas/liquid. The gas/air heat exchange system uses the air preheated in the previous cremation to feed back into the cremator as combustion air, usually during the start-up phase to reduce the energy input to the cremator [5,2]. Remaining air is either released to the atmosphere or sent to heat recovery[2]. Gas/liquid heat exchange systems recover energy via heat transfer from the hot flue gas to a liquid circuit. The energy recovered can be used within the crematoria for needs such as heating and service water heating[2].

To ensure sufficient cooling of temperature peaks from the cremation, the heat exchanger has to be designed with higher capacity on one side. On the other side, the system has to be equipped with a partial flow bypass to avoid temperature falling below dew-point level, especially during start-up procedure. By this integrated heat exchanger bypass the flue gas temperature at the outlet of the heat exchanger can be controlled in an effective way to ensure a stable temperature profile for the flue gas cleaning (see Figure 2-6).

Figure 2-6 Indirect flue gas cooling scheme



Source: Schetter/Djeradi (2013) [23]

Figure 2-7 Indirect flue gas cooling

Source: Schetter/Djeradi (2013) [23]

To minimise PCDD/F formation during flue gas cooling a short residence time within the heat exchanger must be ensured. Therefore, heat exchangers must be designed in a compact way, using straight-tube as well as finned-tube bundles. Depending on the type of cremator, type of subsequent flue gas cleaning and operation condition (cremation rates, coffin weight) the designed capacity of the heat exchangers should be at least 600 kW and can exceed 1000 kW.

Flue gas from cremators include dust particles which may remain on the surfaces of the tube bundles and in consequence will reduce the heat transfer. Therefore, the heat exchanger bundles have to be cleaned periodically. This can be done manually by the operators (at least every two weeks) or automatically by soot blowers using compressed air with about 10 to 13 bar. By applying soot blowers, intervals of manual cleaning can be increased to three or more months.

To reduce greenhouse gas emissions, heat exchangers can be combined with closed water cycles to recover heat from cremation. A mean 200 - 300 kWh per cremation can be utilised as shown by measurements in the crematorium of Schwäbisch Hall (Germany)[25]. Compared

[25] Schetter, G., Lutz, J.: Energieeffizienz und CO_2-Fußabdruck von Krematorien, Bestattungskultur, Heft 10, FVB Verlag, Düsseldorf, 2022

with heat generation by a gas boiler this heat recovery corresponds to a reduction of 40 - 60 kg CO_2 per cremation.

2.2.4. Flue gas cleaning and discharge

The emissions resulting from cremations are similar to those resulting from any combustion process. Additionally, cremation fuelled by natural gas or fuel oil will result in emissions expected from fossil fuel combustion.

Organic pollutants can be formed due to incomplete combustion or reaction of organic compounds and chlorine. Heavy metal emissions result from volatilisation of metals present in body tissues, with mercury emissions mainly resulting from dental amalgam. Further emissions that relate to the materials being combusted will also be released, these can vary within each cremation depending on the materials present. Common pollutants present within crematoria flue gas are:

- **Combustion gases**: Carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and volatile organic compounds (VOC) respectively total organic compounds (TOC)
- **Particulate matter and fine dust**: PM_{10} and $PM_{2.5}$
- **Organic pollutants**: polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs), polycyclic aromatic hydrocarbons (PAHs)
- **Heavy metals**: Mercury (Hg)

A range of flue gas cleaning techniques can be used within the cremation system to control and reduce the emissions of various pollutants or particles simultaneously. Filtering separators, sorption processes and catalytic processes are techniques applied in crematoria depending on the objectives for emissions control and on national, regional or local emission limits[2]. Mercury abatement techniques are explored in detail in Section 3. This section presents only a high-level overview.

Dust is abated through cyclones and/or filtering separators i.e. secondary emission control measures. PCDD/F is abated through both primary measures (control through requirements for the coffin and dead body, minimum temperature in the post-combustion chamber) and secondary measures (abatement techniques). The full range of potential techniques for abating mercury within flue gas treatment is detailed in Section 3.

Certain operational parameters such as temperature, dust (by opacity), carbon monoxide and oxygen are monitored during the cremation. These data allow making adjustments to the combustion process and help achieving the desired operation standards and emission limit values[26].

Following treatment, flue gas is discharged to the atmosphere via a measurement section and stack. The measurement section accommodates sampling for continuous emission monitoring systems.

The release of pollutants from the stack plays a role in the dispersal and ultimate fate of pollutants in the environment. Unabated crematoria do not have mercury specific removal techniques, although the chimney stacks do have specific design implementations to aid in the dispersal and dilution of pollutants e.g. consideration of height.

New crematoria which are fitted with abatement techniques may have a smaller chimney height than those of unabated crematoria. This is because the height is determined as being suitable for releasing abated gases. Abated crematoria (both newly built and retrofitted) have emergency bypass systems in the case of plant failure, power outage or breakdown of abatement equipment.

2.2.5. Bypass

Bypass is a system to release unabated gases in the event of failure of the abatement equipment. These systems vary depending on whether the crematorium is a retrofitted (existing crematoria fitted with abatement) or a new abated crematorium.

For newly built abated crematoria the unabated gases can 'bypass' the abatement plant and release via the emergency release vent (ERV). ERV are not to be used during normal operation of the cremation, however, may be used during warm-up and shutdown provided compliance is demonstrated. ERVs are designed at the optimum height for dispersal of unabated emissions.

Retrofitted crematoria may also use an ERV system to release to atmosphere if this is within the design of the plant. Alternatively, the original chimney may be used as a bypass route to release gases. The original chimney will have been designed to optimum height for release of unabated gases, and so is usually sufficient to use in event of emergency.

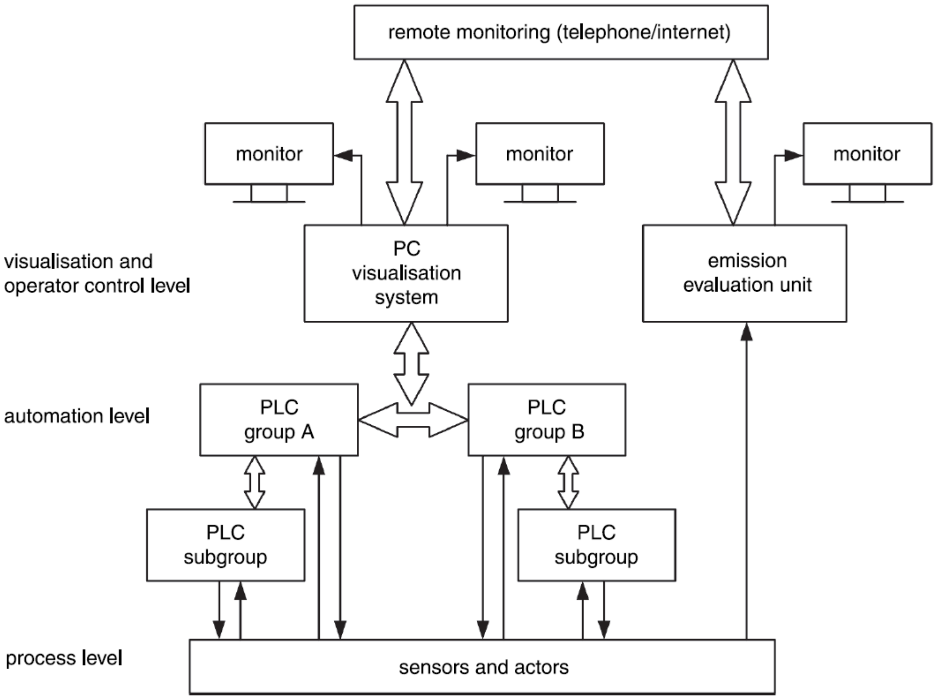
During normal operation, the bypass must be closed, with the actuator of the bypass damper/valve designed to function in the case of an abnormal condition e.g. power loss.

[26] Australian Government, National Pollution Inventory Emission Estimation Technique Manual For Crematoria, Version 1.0, Canberra, 2011 https://www.dcceew.gov.au/sites/default/files/documents/crematoria.pdf

2.2.6. Process control

The process control system (PCS) is used to control, regulate and monitor the intended operation and must also fulfil safety-related tasks. Its main goals are the protection of the operating staff, the protection of the plant components and compliance with the legal authorisation requirements, in particular the emission limit values. A process control system is organised into three levels: process level, automation level and the visualisation and operator control level. All elements of the control system shall ensure the collection of sensitive measurement data and fast translation into action[27].

Figure 2-8: Schematic of process control system and the organisational levels



Source: VDI (2015) [8]

The automation level uses programmable logic control (PLC) to integrate all process-relevant information centrally, enabling automation of the plant[27]. Within the visualisation and operator control level, logging and visualisation of control interventions, fault and status parameters of the process are displayed graphically to enable observation and controlled intervention of the cremation process[27].

The process control system is unique to each crematorium as it is matched to the specific process of the plant and must combine the cremator and flue gas treatment system in an integrated control concept. A safety strategy must be in place and the process control

[27] VDI-Richtlinie 3891:2015 Emission control - Human cremation facilities. VDI e.V., Düsseldorf, 2015

system must meet the following objectives: protection of operating personnel, compliance with permit conditions specifically the emissions limit values, and the protection of plant equipment. Independent hardware or software controls have to be implemented for safety-relevant functions in accordance with requirements and technical rules. Furthermore, an uninterrupted power supply (UPS) system must be in place to secure voltage supply of the control process levels (visualisation, operator control and automation)[27].

2.2.7. Emission monitoring

Emissions from the cremation process may be continuously (e.g. via sensors or automatic analysers for pollutants such as CO, dust, SO_2, or NOx) or non-continuously measured (e.g. via sampling and external measurement of pollutants such as mercury and dioxins/furans) to control the performance of the flue gas treatment as well as to check compliance with emission limit values.

Process control in crematoria depends on legal requirements. Several European countries require continuous monitoring of temperature and oxygen content to ensure the legal minimum temperature in the post-combustion unit (e.g. Belgium, Denmark, France, Germany, Italy, Norway, Spain, Sweden, Switzerland, The Netherlands, and UK). In most of these countries, this is combined with a continuous monitoring of CO emissions to ensure an extensive combustion of organic compounds and compliance with CO emission limit values (ECN 2018[28], BImSchV 2013[29]). Other parameters are monitored periodically, either annually, biannually or triennially, depending on the national emission limits and on parameters. Dust and PCDD/F are most controlled parameters, followed by NOx, SO_2, HCl, TOC and mercury (ECN 2018).

2.2.8. Ash processing unit

The ash processing unit is where the bone fragments are ground into ashes after a period of cooling and filtering. The cooling period can take between 30 minutes to an hour after which the fragments are then able to be filtered. The filtering process removes any metals remaining after cremation, such as tooth fillings and coffin parts, by passing the remains through a magnetic field[30]. This process previously was done by hand by an operator using a strong magnet to remove metals on an ash processing table, then moving them to an ash

[28] ECN 2018: Chart comparing the regulatory demands of European countries with regard to the atmospheric emissions of crematoria, European Cremation Network https://dfweurope.com/wp-content/uploads/2018/01/ECN-chart-comparing-atmospheric-emissions-of-crematoria.pdf

[29] BImSchV 2013: Siebenundzwanzigste Verordnung zur Durchführung des Bundes-Immissionsschutz-gesetzes - Verordnung über Anlagen zur Feuerbestattung (German Ordinance on Crematoria), 2013

[30] Cremation Solutions, see more information here: https://www.cremationsolutions.com/information/scattering-ashes/all-about-cremation-ashes/

processor[31]. More modern processors are able to separate the metals from the bone fragments without the need for manual processing. These processors also automatically fill any type of urn. These are used in crematoriums throughout Europe including the Netherlands, Belgium, Germany, France, Italy, Austria, England, Spain and Ireland[32].

2.2.9. Alternative methods of cremation

While the prevailing method of cremation throughout Member States produces ashes, there are emerging techniques being developed as alternatives to flame cremation methods. These are summarised below.

2.2.9.1. Alkaline Hydrolysis

An alternative to flame cremation is alkaline hydrolysis, which is practiced across America and Canada. Alkaline hydrolysis may also be known as water cremation, liquid cremation, resomation, flameless cremation or green cremation. Only the body enters the cremation chamber and not the coffin. Additionally, prosthesis and pacemakers do not have to be removed before the hydrolysis process begins and are recovered after the hydrolysis is complete. The process takes place in only one chamber which is relatively small in size compared to flame cremation ovens.

The body is placed in a closed vessel (a so-called resomator) alongside 95% water mixed with 5% alkaline solution, this is where the alkaline hydrolysis will take place. To break down the body tissues and organic matter the resomator is heated and agitated which aids and accelerates the decomposition process[33]. The process breaks down tissues and dissolves them into a liquid solution, while leaving behind bones. The bones can then be processed into ashes in the same way as in flame cremations. Overall, the process takes around 4 hours, with the outputs of the process being sterile bone ash and liquid which is drained away into mains water after rigorous processing through filtration and purification[34]. Due to the use of heat, there are emissions to air produced, however these are fewer than those

[31] Cremation Equipments, see more information here: https://cremationequipments.com/ash-processing/

[32] DFW Europe, see more information here: https://dfweurope.com/cremulator/

[33] Pure Reflections, The Human Body and Alkaline Hydrolysis: Restoring Nature's Balance; 2023. https://www.purereflections.ie/post/the-human-body-and-alkaline-hydrolysis-restoring-nature-s-balance

[34] Funeral Guide, 2023, A Guide to Water Cremation https://www.funeralguide.co.uk/help-resources/arranging-a-funeral/funeral-guides/a-guide-to-water-cremation

produced in flame cremation. The fate of dental amalgam during the process remains unclear as no specific mercury-specific control measures are documented[35,36,37].

Alkaline hydrolysis is not legal in most EU Member States and only one resomorium exists within Europe which is located in the Republic of Ireland[38].

2.2.9.2. Terramation (Human Composting)

Another alternative to flame cremation is terramation, also known as human composting or natural organic reduction, which relates to the process of transforming human remains into soil. Similarly to alkaline hydrolysis, this is a process of accelerated decomposition, however this process is slower, taking several weeks.

The body is prepared in a specific vessel with a mixture of wood chips, alfalfa (lucerne plant) and straw. Once the body has been prepared and covered in this mixture, the vessel is closed to begin decomposition, over five to seven weeks. During this time, microbes already naturally present transform the remains into nutrient dense soil, the vessel may also be rotated to ensure aeration during this phase. After this process the soil is then removed from the vessel and cures over the next three to five weeks[39]. During the composting process bones and teeth do not fully break down, therefore the bones are milled to a fine powder and returned to the compost. There is a screening for non-organic material during this step which can be recycled. It is unclear what the fate of non-recyclables and there is no information on amalgam fillings and the fate of the mercury they contain.[39] Terramation is adopted in some states across America, however currently only one EU Member State (Sweden) and the northern region Schleswig-Holstein in Germany offer a form of terramation as a funeral solution[40, 41].

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[35] Pure Reflections, Ensuring Environmental Responsibility: The Safe Water Management in Resomation Processes, 2023 https://www.funeralguide.co.uk/help-resources/arranging-a-funeral/funeral-guides/a-guide-to-water-cremation

[36] Pure Reflections, What is Resomation, 2022 https://www.purereflections.ie/post/what-is-resomation

[37] Pure Reflections, 2023, Resomation: Eco-Friendly alternative https://www.purereflections.ie/post/resomation-eco-friendly-alternative

[38] Pure Reflections https://www.purereflections.ie/

[39] Recompose, 2024 https://recompose.life/our-model/#the-process

[40] Recompose, 2024 https://recompose.life/human-composting/legal-status/

[41] Der Streit um die "Reerdigung" – sollten wir uns nach dem Tod kompostieren lassen? MDR, 27.3.2022 https://www.mdr.de/nachrichten/deutschland/panorama/reerdigung-nachhaltige-bestattung-preis-ablauf-sicherheit100.html (24.10.2024)

2.2.9.3. Promession

Promession reduces the human body into powder by freezing the body using liquid nitrogen. The first step of the process is to place the body in a coffin, which is then moved inside the cremation chamber. In this chamber the body is frozen to around -18 ^{0}C, once the body is completely frozen the coffin and body are moved to a platform. This platform is inside a sealed ‘promator’ machine, which moves the coffin and body through each stage of the process. The coffin is first weighed to calculate the amount of liquid nitrogen required, then the liquid nitrogen is used to freeze the body to -196 ^{0}C. This process takes around 2 hours to allow the body to fully freeze and reach the correct temperature. The body is transferred to another unit for ultrasonic vibration, which turns the body into a powder similar to ashes. The final step is to move the powder into an evaporation chamber to allow water to evaporate, leaving the dry powder behind. To remove any metals (dental fillings, jewellery and prosthesis) the powder is filtered and then placed in a biodegradable coffin[42].

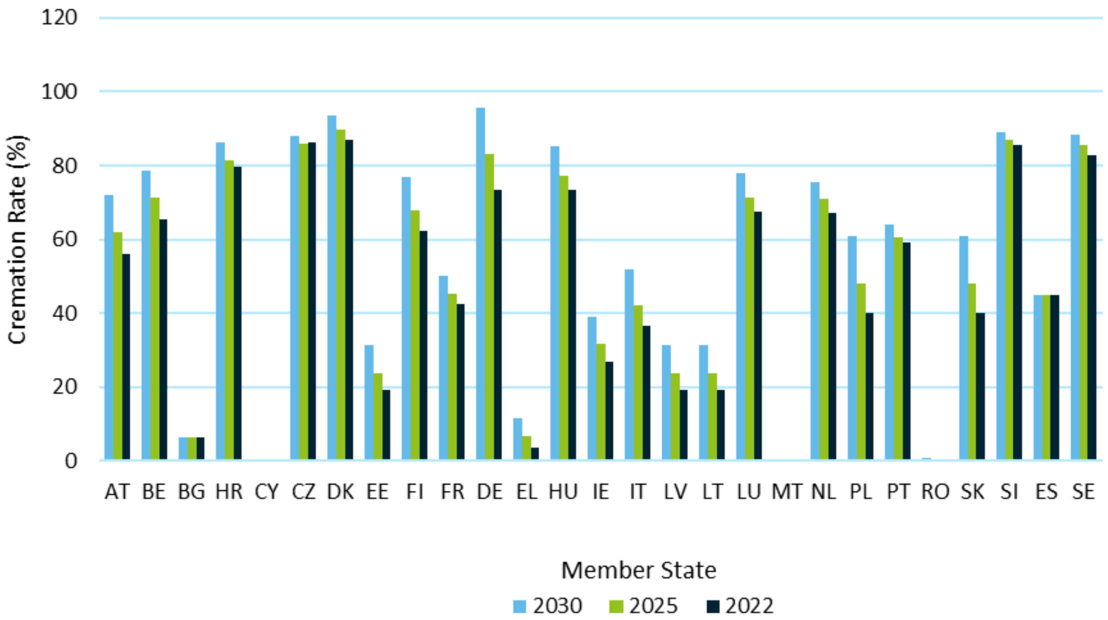
[42] Promessa, 2020, ‘Ecological burial’. https://promessa.se/

2.3. Mercury emissions from cremation in the EU

The impact assessment[43] in support of the Revision of the Mercury Regulation[44] conducted a bottom-up modelling approach to quantify mercury emissions using trends and activity levels. This has been updated in this document using more recent data.

The latest data on national annual cremation rates[45] are shown in Figure 2-9.

Figure 2-9: National annual cremation rates, 2022, 2025 and 2030[46]



The estimated mercury content of corpses was also updated, taking into account the ban on the use of dental amalgam from 1st January 2025 according to the revised Mercury Regulation and considering the use of derogations in relation to this ban as invoked by the Czech Republic and Slovakia (Figure 2-10). The figures indicate that the mass of mercury reaching crematoria is decreasing from 2022 to 2030 in most Member States.

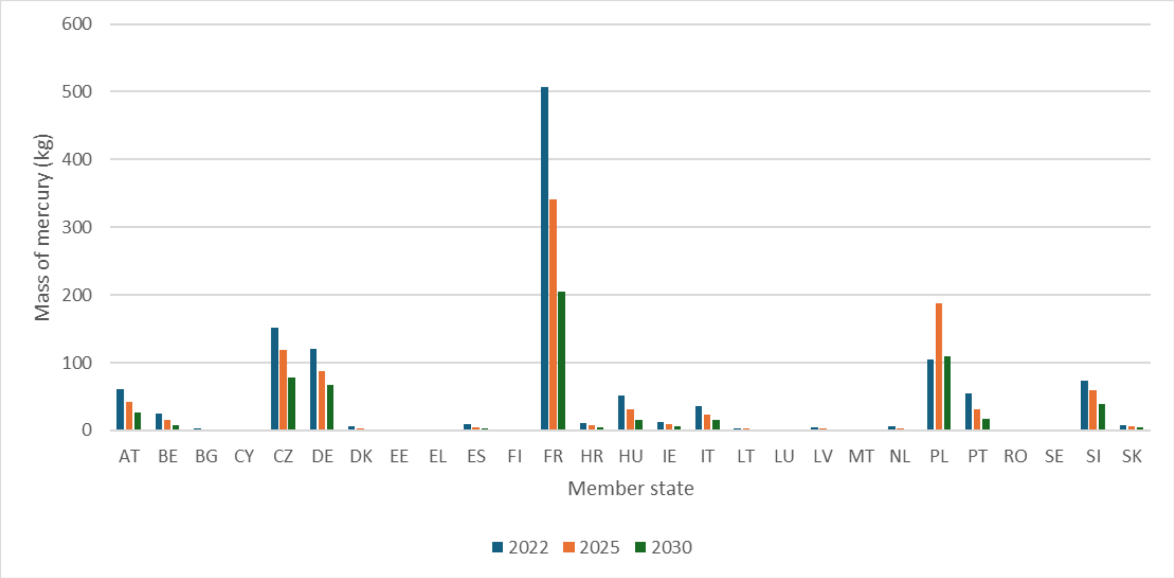
[43] Impact Assessment Report, EU Commission Staff Working Document, Brussels, 14.7.2023 https://ec.europa.eu/transparency/documents-register/api/files/SWD(2023)396_0/090166e5feabf75e?rendition=false

[44] Proposal for a revision of the Mercury Regulation https://environment.ec.europa.eu/publications/proposal-revision-mercury-regulation_en

[45] International Cremation Statistics 2023, The Cremation Society, Kent/UK, 2024 https://www.cremation.org.uk/International-cremation-statistics-2023

[46] Data obtained from The Cremation Society (2021). https://www.cremation.org.uk/ In the absence of cremation rates for the following Member States, rates for other Member States were used as a proxy: Bulgaria (Romania used as proxy); Latvia and Estonia (Lithuania used as proxy); Croatia (average of Hungarian and Slovenian rates used); Slovakia (Czechia used as proxy).

Figure 2-10: Masses of mercury in corpses reaching crematoria, 2022, 2025 and 2030 – central estimates



Estimated crematoria mercury emissions were updated using available information on mercury abatement techniques fitted at an EU27 (Figure 2-11) and Member State level (Figure 2-12).

Total mercury emissions for the EU27 are estimated at 529kg in 2022, with a lower estimate of 233kg and an upper estimate of 931kg. Emissions at EU level are forecast to gradually decline to 491kg in 2025 and 300kg in 2030.

Figure 2-11: Estimated mercury emissions from crematoria for EU27 in 2022, 2025 and 2030

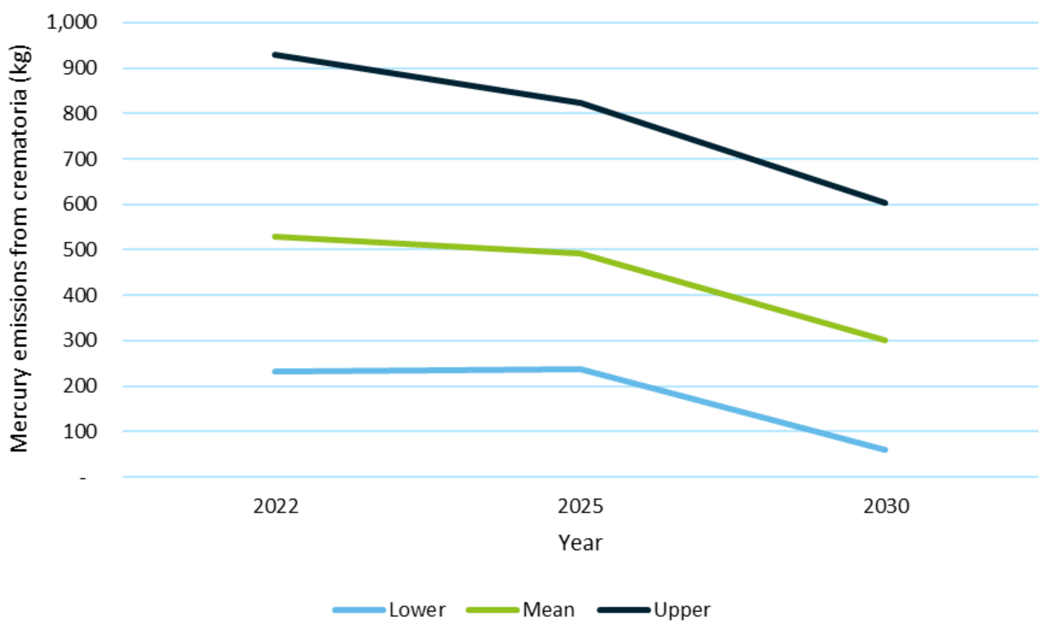
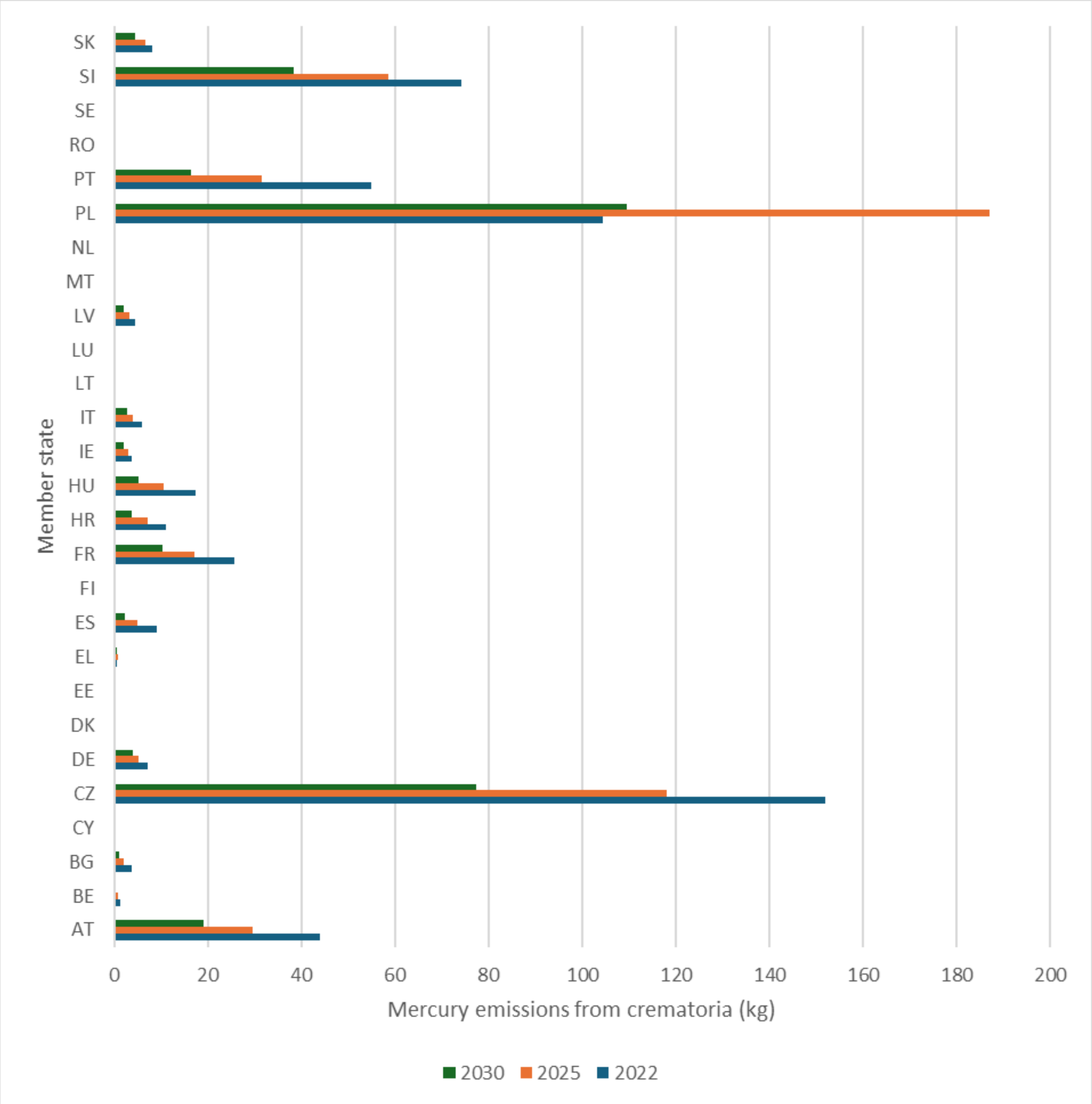


Figure 2-12: Estimated mercury emissions from crematoria per Member State in 2022, 2025 and 2030



3. Best Available Techniques for mercury reduction

3.1. Introduction

Depending on national, regional or local requirements, crematoria are equipped either without waste gas treatment systems or with a cooling system combined with waste gas treatment. Cooling to below 140°-150°C is needed to protect the subsequent treatment systems. Additionally, cyclones may be installed to protect a fabric filter from embers.

Mercury abatement techniques therefore are normally part of a broader system of cooling and abatement techniques of other pollutants (see Table 3-1).

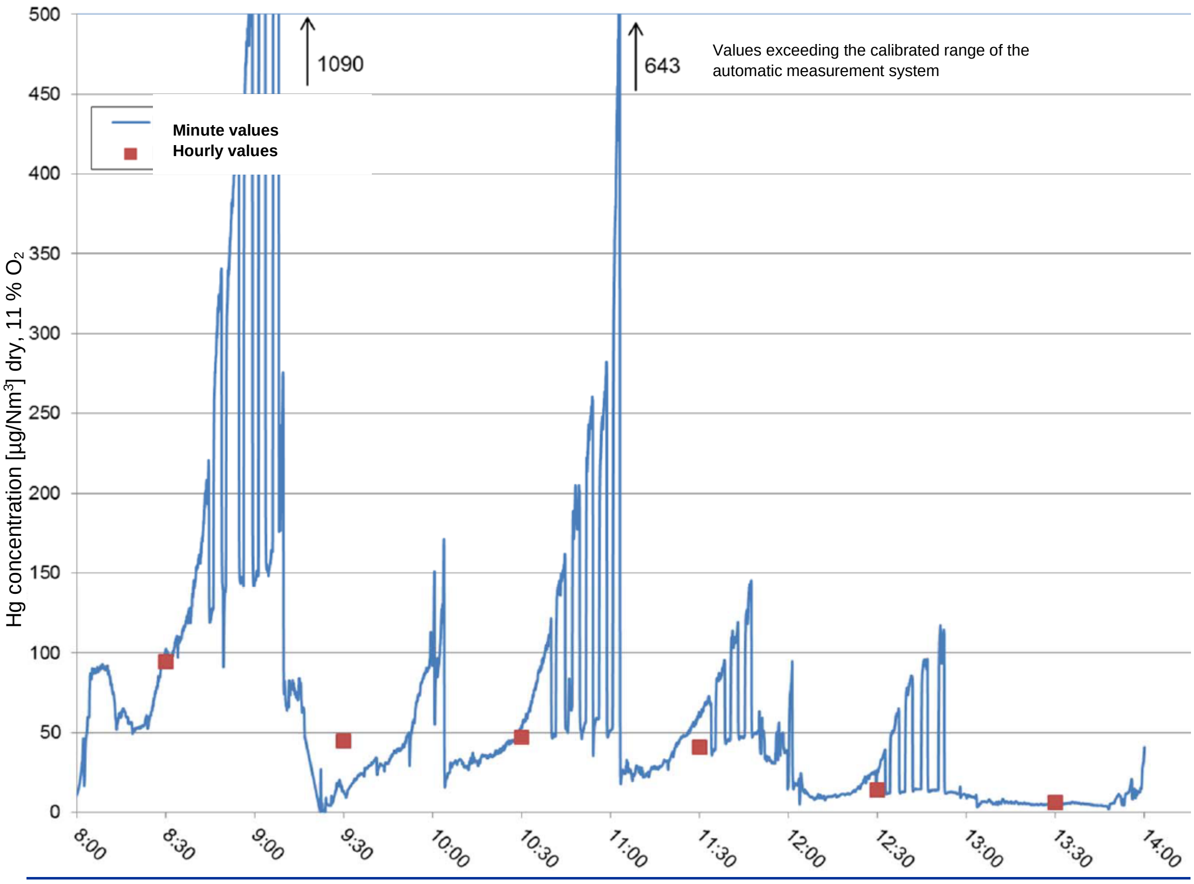
Table 3-1: Most frequent combination of waste gas treatment systems in crematoria

	Cooling (optional)	Cyclone (optional)	Conventional fabric filter	Catalytic fabric filter (alternative)	Use of activated carbon (fixed bed or sorbent injection)
Main effect	Protection of fabric filter from excessive heat	Protection of fabric filter from embers	Reduction of dust and dust-bound pollutants	Oxidation of PCDD/F and NOx	Reduction of PCDD/F and Hg
Effect on Hg	Gaseous Hg condenses on particles	Reduction of Hg bound on large particles	Reduction of dust-bound Hg	Reduction of dust-bound Hg	Reduction of gaseous Hg
Total Hg reduction	None	Low as most Hg is gaseous	Low as most Hg is gaseous	Low as most Hg is gaseous	Medium to high

Other techniques for waste gas abatement in crematoria are rarely used and not proven to be effective for mercury, such as wet scrubbers, the addition of selenium, or amalgamation with metals.

Mercury from crematoria is not emitted continuously but rather associated with short and high peak emissions after break of the coffin, and low mercury emissions during the rest of a cremation (typically lasting about one hour). Peak emissions vary significantly according to the number of amalgam fillings of a body. Figure 3-1 shows typical variations of peak emissions with minute values (blue line) and hourly mean values (red dot). These variations are a challenge for all mercury reduction techniques.

Figure 3-1: Mercury emission variations in 6 hours of crematorium operation [µg/Nm³, 11 % O_2]



Source: Bittig/Haep (2018)[47]

3.2. Summary of mercury abatement techniques

Table 3-2 provides an overview on potential techniques for mercury reduction that were considered for BAT. Because on a combination of 1) their general applicability, existing application in the sector and several EU providers 2) their proven mercury abatement efficiency, techniques assessed to be BAT are:

- Activated carbon fixed bed filters
- Activated carbon sorbent injection

[47] Bittig, M., Haep, S.: Quecksilberemissionen aus Krematorien – Welchen Herausforderungen muss sich die Abgasreinigung stellen? In: Krematorien - Quecksilber und andere Umwelteinflüsse, Schetter, G. (Ed.), ISBN 978-3-936057-62-1, FVB Verlag, Düsseldorf, 2018

In addition to these above techniques, application of selenium filters and sorbent polymer composite systems are assessed to be emerging techniques for mercury abatement in crematoria. This is because of their successful application for high mercury abatement in non-ferrous metal plants and waste incineration/power plants, and high mercury abatement potential.

Table 3-2 shows a summary of mercury abatement techniques, including those assessed as BAT as well as other techniques which have been screened out on the basis of poor/unsuitable abatement of the high peak mercury emissions in crematoria, and/or low applicability to the sector. A number of techniques that have historically been included in guidance such as OSPAR 2003 [48] and Helcom[49] guidance are not assessed as BAT. This includes gas scrubbing and gold filters. These techniques have not been assessed as BAT due to lack of evidence for their effectiveness in abating mercury emissions from crematoria, and lack of availability/EU technique suppliers.

[48] Mercury emissions from crematoria and their control in the OSPAR Convention Area, OSPAR Commission, London, 2003 https://www.ospar.org/documents?v=6971

[49] Reduction of emissions from crematoria. HELCOM Recommendation 29/1, Baltic Marine Environment Protection Commission, Helsinki, 2008 https://helcom.fi/wp-content/uploads/2019/06/Rec-29-1.pdf

Table 3-2: Overview on techniques for mercury removal

Technique	Abatement	Applicability and availability	Complexity and need for additional systems
1 Fixed bed filter after fabric filter (BAT)	**Medium to high mercury abatement** (88-99%) Co-benefits: PCDD/F	**Generally applicable**. Several providers. High Hg reduction if sufficient sorbent and bed changed on time.	Very simple system to operate. Requires upstream cooling and dust cleaning. Requires by-pass and additional upstream cooling with specific temperature control to avoid self-ignition. Includes reduction of organic compounds like PCDD/F.
2 Sorbent injection before fabric filter (with/without sorbent rotor cycle system) (BAT)	**Medium to high mercury abatement** (78%-99%) Co-benefits: PCDD/F, dust	**Generally applicable**. Several providers. High Hg reduction if sufficient sorbent.	Simple system to operate. Includes dust cleaning. Requires upstream cooling. Includes reduction of organic compounds like PCDD/F.
3 Fabric filters or catalytic fabric filters	Low for gaseous Hg (used mainly for PCDD/F removal; only removes dust-bound mercury) Co-benefits: Dust	**Limited applicability (catalytic filter).** One provider. Not efficient for reduction of gaseous Hg.	Very simple system to operate. Includes dust cleaning and reduction of organic compounds like PCDD/F.
4 Wet scrubber	Low for gaseous Hg Simple systems using water only reduce oxidised mercury and therefore only achieve limited reduction efficiency Complex wet scrubber systems use oxidising agents to reduce elemental mercury but require highly skilled staff for operation, usually not available in crematoria.	**Limited applicability (few applications in crematoria).** Several providers. Hg reduction effective if only well managed. Generates visible plume.	Complex system to operate as re-emission of mercury is only hindered if chemicals are used and very well managed with highly skilled staff. Dust cleaning is not satisfactory. No data regarding cleaning efficiency for organic compounds like PCDD/F. Generates liquid waste requiring treatment before disposal.

Technique	Abatement	Applicability and availability	Complexity and need for additional systems
5 Selenium addition	Not proven	No longer used as inefficient	Simple system to operate. Potential environmental impact in case of emissions of selenium oxide. Requires upstream system for removal of dust and organic compounds like PCDD/F.
6 Selenium filter (Emerging technique)	High (potentially). Not sufficient data to evaluate whether Hg from crematoria is reduced efficiently.	**Potentially applicable** One provider but not providing small systems for crematoria. Not used in crematoria but in non-ferrous metal plants	Simple system to operate. Requires upstream system for removal of dust and organic compounds like PCDD/F (e.g. catalytic filter). Requires service for recovery of the selenium filter.
7 Sorbent Polymer Composite (SPC) (Emerging technique)	High (potentially). Not sufficient data to evaluate whether Hg from crematoria is reduced efficiently.	**Potentially applicable.** One provider. Not used in crematoria but in power plants.	Simple system to operate. Requires upstream cooling and system for removal of dust and organic compounds like PCDD/F (e.g. catalytic filter).
8 Boliden Norzinc process (“chloride process”, “calomel process”)	High (potentially). Not sufficient data to evaluate whether Hg from crematoria is reduced efficiently.	**Difficult to apply.** One provider but not providing small systems for crematoria. Not used in crematoria but in non-ferrous metal plants	Complex system to operate. Requires management of hazardous chemicals (H2SO4, Cl2) by highly skilled staff. Requires upstream system for removal of dust and organic compounds like PCDD/F.
9 DOWA filter (“lead (II) sulphide process”)	High (potentially). Not sufficient data to evaluate whether Hg from crematoria is reduced efficiently.	**Not applicable** No more providers. Not used in crematoria but in non-ferrous metal plants	Simple system to operate. Use of a highly toxic compound (PbS). Requires upstream system for removal of dust and organic compounds like PCDD/F.
10 Amalgamation (“gold filter”)	Not proven	**Not applicable** No more providers Not used (except for analysis of mercury)	Simple system to operate. Requires upstream system for removal of dust and organic compounds like PCDD/F (e.g. catalytic filter). Requires service for recovery of amalgamation system.

Source: Dehoust et al. (2020)[50] , VDI 3891:2024 [52]

[50] Dehoust, G.; Gebhardt, P.; Tebert, C.; Köser, H.: Quecksilberemissionen aus industriellen Quellen – Status Quo und Perspektiven (Teil 2). Umweltbundesamt (Ed.), Texte 68, Dessau-Roßlau, 2020 https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021-04-26_texte_68-2021_quecksilberemissionen_teil_2_0.pdf

3.3. Fixed bed filter (“solid bed filter”, “activated carbon filter”)

3.3.1. Short description

A fixed bed filter is a bed of sorbent material to capture mercury by physical adsorption and chemisorption mechanisms. The sorbent material must be replaced after service life. As at least a share of the sorbents consists of activated carbon or coke, the filter is also called “activated carbon filter”. The technique is mentioned in OSPAR Recommendation 2003/4 [51].

3.3.2. Technical description

A fixed bed filter uses containers filled with sorbents consisting of activated carbon or coke and potentially mixed with inert sorbents to clean the flue gas from mercury, PCDD/F and other pollutants. The flue gas must be cleaned from particulates by a fabric filter to avoid clogging and reduction of the active surface of the sorbent in the fixed bed. The flue gas also requires cooling to a temperature range of about 80 to 140 °C before entering the fixed bed [52].

Fixed bed filters must be designed in such a way that a uniform gas flow through the fixed bed is achieved. Partial circulating back flow of flue gas must be avoided. In consequence a flow grid at the entrance of the fixed bed filter is usually used (see Figure 3-2). The bed length (height) for the application in crematoria is in the order of 0.8 to a maximum of 1.2 m to avoid too much pressure drop [52].

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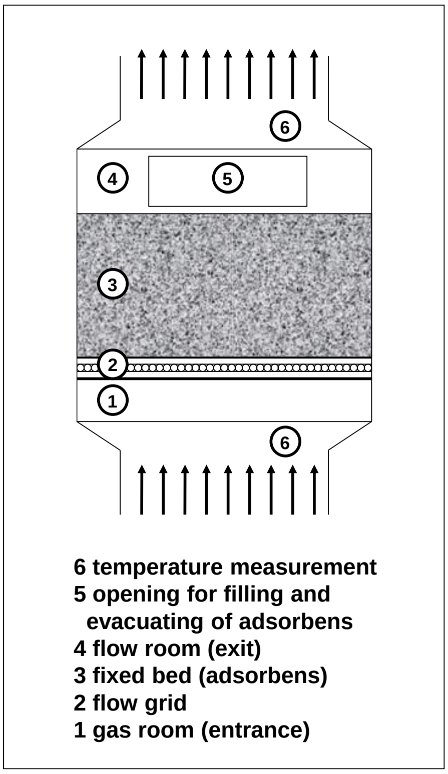
[51] OSPAR Recommendation 2003/4 on Controlling the Dispersal of Mercury from Crematoria, OSPAR Commission, London, 2003

[52] VDI-Richtlinie 3891:2024 Emission control - Human cremation facilities, Final draft, VDI e.V., Düsseldorf, September 2024

Figure 3-2: Fixed bed filter scheme



Source: Reichart, A.; Schetter, G. (2014)[53]

Figure 3-3: Fixed bed filter

Source: Reichart, A.; Schetter, G. (2014) [53]

[53] Reichart, A.; Schetter, G.: Erfahrungen mit dem Einsatz von Festbettfiltern in Krematorien. In: Krematorium – Emission und Energie, ISBN 978-3-936057-45-4, FVB Verlag, 2014

The maximum load capacity of a fixed bed filters is first reached in the lowest layer of a fixed bed. Therefore, a system variation as moving bed filter was developed.[54] Apparently, the system was not installed in many crematoria and stopped operation after some years, e.g. in Lucerne and in Winterthur (Switzerland). The system included a periodic removal of the lowest filter bed material, combined with parallel manual filling on top with new material. However, suppliers report difficulties resulting from corrosion of the “seashell” flaps for sorbent removal. Hence the filters were preferred to be operated as fixed beds.

Another system variation was the development of a two-section fixed bed filter, installed in Meißen (Germany), with one section for mercury sorption on activated coke and a second section with zeolite for PCDD/F adsorption. The idea was to recover the zeolite by PCDD/F treatment (thermally or with oxidants) and to reduce both the risk of self-ignition and the volume of activated carbon loaded with mercury. Measurement showed that the reduction efficiency for mercury decreased from 94 % to 65 % after 1200 cremations.[55] No further installations are known with a similar system.

The use of activated carbon in fixed bed filters implies a risk of self-ignition. Therefore, an activated carbon fixed bed filter must not be operated at temperatures above 140°C. Cooling may be realised with two levels, a higher one for the fabric filter (max. 200°C) to avoid condensation and a subsequent second one to finetune for the fixed bed filter (max. 140°C).

To reduce the risk of self-ignition, activated carbon may be mixed with inert material, typically lime or lime hydrate. This can reduce acidic pollutants like sulphur oxides, chloride and fluoride.

Chemisorption and adsorption are effectively reducing elemental mercury and oxidized mercury. Oxidised mercury can be removed with high efficiency by the physical mechanisms of adsorption. To remove elemental mercury chemisorption is necessary, which can be achieved by impregnating the sorbent material with sulphur (S) or sulphuric acid (H_2SO_4) for example. Table 3-3 shows examples of sorbent materials used in fixed bed filters for mercury and PCDD/F removal. The smaller the grain size of the sorbents the shorter the distance to inner pores, however the greater the pressure drop of a filter.

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[54] Esser-Schmittmann, W.; Scheele, S.: Abscheidung von Quecksilberemissionsspitzen in Krematorien durch Adsorption, in: Krematorium – Quecksilber und andere Umwelteinflüsse, ISBN 978-3-936057-62-1, FVB Verlag, 2018

[55] List, S.; Schaldach,J.: Die Entwicklung der Festbettfiltertechnik – Erfahrungen mit einem 2-Schichtfilter im Krematorium Meißen, Workshop Krematorien, 2007 https://www.krematorium-meissen.de/umweltschutz.html?file=files/Downloads/Workshop_Krematorien_Tagungsband.pdf&cid=4001

Table 3-3: Examples of sorbent materials for fixed bed filters

	Coke from lignite [%]	Activated carbon [%]	Lime hydrate [%]	Pumice [%]	Grane size [mm]
Coke	100				2,5 - 8
Activated carbon		100			2,5 - 8
Activated carbon		100			4 (cylinder coke)
Sorbalit ® G 35%	35		65		2 - 6
Cremitec ®	50			50	3 - 5

Source: Esser-Schmittmann, W.; Scheele, S. (2018)[54]

To characterize the surface characteristics of activated carbon, the method by Brunner, Emmett and Teller is used determining the “BET value“ (see Table 3-4). To improve chemisorption of elemental mercury, the sorbents may be impregnated with sulphur, bromide or iodite.[56]

Table 3-4: Typical surface characteristics of sorbents

Sorbent type	BET [m^2/g]
Activated carbon	600 – 850
Activated coke	300
Bentonite	50 – 150
Zeolite	40 – 90
Lime	15 – 45
Pumice	< 10

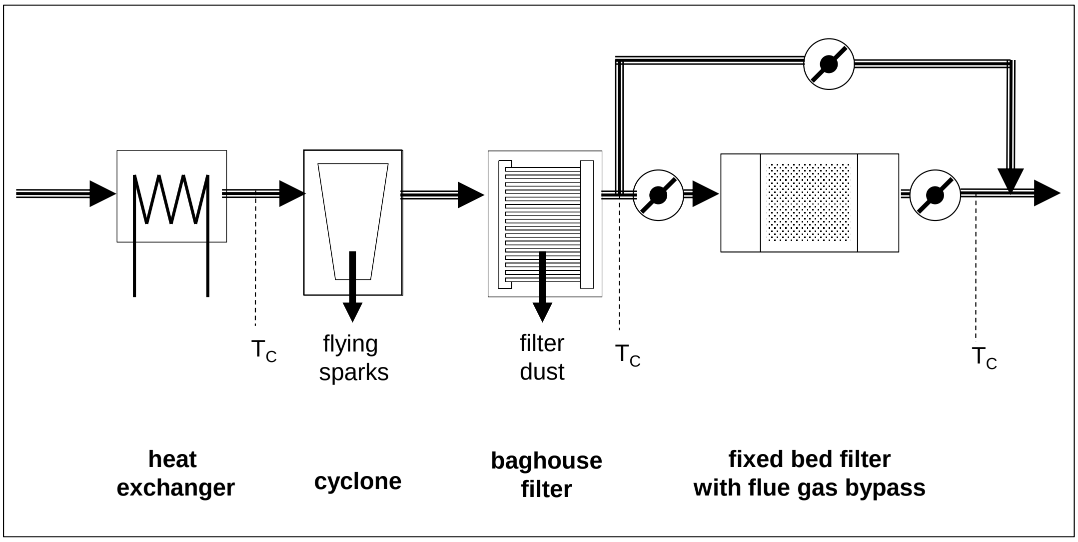
Source: Esser-Schmittmann, W.; Scheele, S. (2018)[54]

Fixed bed filters are passive systems (no moving parts such as compressors or motors), therefore not requiring continuous operational assistance. However, flue gas temperature must be monitored continuously to avoid the risks of self-ignition and desorption of mercury and other pollutants like PCDD/F.

Fixed bed filters require a flue gas bypass (see 2.2.5). This safety equipment ensures that in case of temperatures above 140°C, self-ignition and desorption of removed pollutants are avoided by directing the flue gas through the bypass to the stack.

[56] Esser-Schmittmann, W. (2012): Quecksilberabscheidung aus Feuerungsprozessen mittels Chemisorption an Aktivkohle und anderen Sorbentien. In: Immissionsschutz, Band 3, TK Verlag, Nietwerder https://books.vivis.de/wp-content/uploads/2023/03/2012_IS_563_574_Esser_Schmittmann.pdf

Figure 3-4: Schematic of a flue gas treatment system with fixed bed filter



Source: Own diagram by Schetter

3.3.3. Achieved environmental benefits

Fixed bed filters reduce organic compounds (e.g. PCDD/F) and mercury efficiently. They also reduce acidic pollutants (HCl, HF, SO_2) if sorbents consist not only of activated carbon but also of other components like lime hydrate.

A fixed bed filter in the beginning has a high excess of removal capacity compared to the amount of mercury passing through the filter. This leads to high removal rates even in case of mercury peaks. However, the removal capacity of a fixed bed decreases over time. If the sorption capacity is exhausted, mercury is no longer removed.

3.3.4. Operational data

Table 3-5 shows typical operational data of fixed bed filters.

Table 3-5: Typical operational data of fixed bed filters

Parameter	Typical values
Temperature of fixed bed	~ 80 – 140°C
Pressure drop	~ 5 – 18 hPa
Raw gas velocity in the bed	~ 0.2 – 0.4 m/s
Effective bed length	~ 0.8 – 1.2 m
Mean sorbent consumption	~ 0.3 – 0.8 kg per cremation

Source: VDI 3891 (2024)[52]

The mercury removal rates are difficult to determine due to

- Extreme variation of mercury concentration in the raw gas (calibrated measurement range of continuous measurement equipment is often exceeded).
- Limited possibilities to fulfil standard measurement conditions for raw gas measurement (generally met in straight flue gas duct sections with an undisturbed inlet section of five hydraulic diameters upstream and an undisturbed outlet section of two hydraulic diameters downstream of the measuring cross-section and a distance to the end of the flue gas duct of at least five hydraulic diameters).
- Limited representativity of a) the mercury input of cremations during the measurement, b) the sorption capacity of the fixed bed filter at the time of measurement (varies over time).

The mercury removal efficiency of fixed bed filters depends on:

- raw gas concentration of mercury,
- sorbent characteristics (grain size determining the outer surface, pore volume determining the inner surface, impregnation leading to chemisorption),
- contact time (length of the bed, flue gas velocity, uniform gas flow through the bed),
- flue gas temperature,
- competing flue gas components (e.g. sulphur dioxide, humidity).

Activated carbon catalytically converts sulphur dioxide in the presence of oxygen and water to sulphur trioxide and sulphuric acid, and the sulphuric acid is retained in their pore system.[57] This hinders physical adsorption of elemental mercury but improves chemisorption of oxidised mercury.

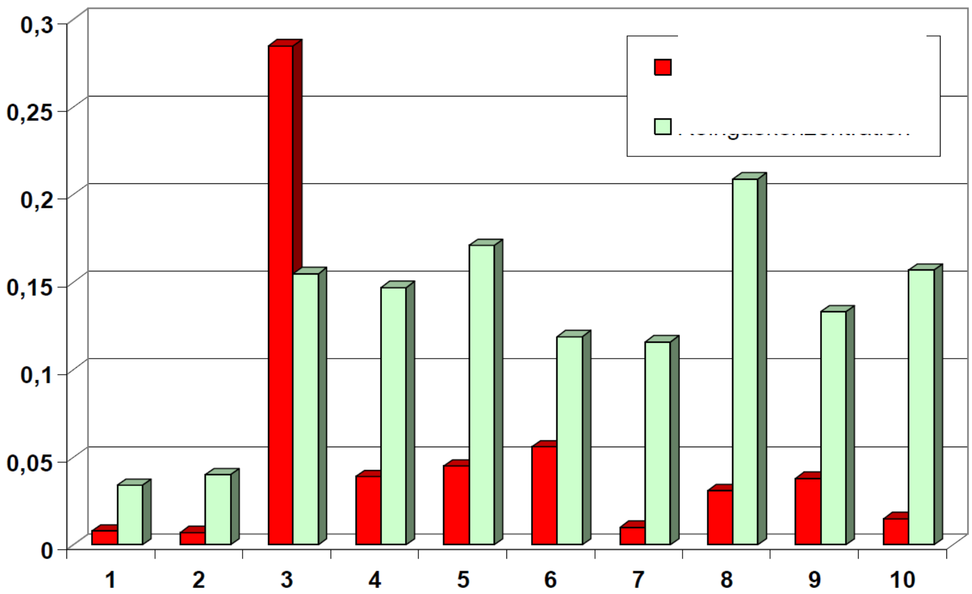
Adsorption of water on the surface of activated carbon only occurs at elevated concentrations of typically more than 60 % relative humidity.[57] Where flue gas cooling is done with water injection, the sorption capacity of activated carbon is reduced accordingly.

Compliance monitoring in Switzerland is done with addition of 3 g mercury in each cremation to monitor compliance with the mercury emission limit value of 0.2 mg/Nm^3 (hourly mean). Monitoring results usually show emission values well below the limit value during the first years after a fixed bed filter is filled and operated, depending on the length of the fixed bed.

[57] VDI-Richtlinie 3891:2024 Emission control - Human cremation facilities, Final draft, VDI e.V., Düsseldorf, September 2024

If the sorbent capacity is exhausted, mercury and other pollutants like PCDD/F can pass and desorb as documented by Schetter (2016)[58] in Pforzheim (Germany). All measurements except no.3 show higher outlet than input values for mercury (Table 3-4). The filter with 2m^3 activated carbon pellets, equivalent to about 1000 kg, had been used for 22 months. With about 30 cremation per day during ~90 weeks, the filter had been loaded with about 2.7 cremations per kilogram sorbent (compare data below and Figure 3-7).

Figure 3-5: Exemplary hourly mercury concentration (raw/clean gas) indicating desorption effects of an overloaded fixed bed filter system in the crematorium of Pforzheim



Note: Raw gas measurement was done on a sampling point not complying with standard conditions. “Raw gas measurement was in many cases near the limit of detection of 0.1 mg/Nm^3”. No information regarding oxygen standardisation. No information on type of sorbent and on sorbent injection rate.

Source: Schetter (2016)[58]

Stöcklein et al. (2016)[59] documented hourly clean gas values (11 % O_2) after fixed bed filters of two crematoria in Germany (without specifying sorbent characteristics and filter dimensions).

[58] Schetter, G.: Langzeituntersuchungen zu Emissions- und Schadstoffminderungen in Krematorien durch veränderte energieeffiziente Betriebsweisen. Deutsche Bundesstiftung Umwelt (Ed.), 2016 https://opac.dbu.de/ab/DBU-Abschlussbericht-AZ-31407.pdf

[59] Stöcklein, F.; Gass, H.; Suritsch, N.: POP- und Hg-Emissionen aus abfallwirtschaftlichen Anlagen. Umweltbundesamt (Ed.), Texte 38, Dessau-Roßlau, 2016 https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_38_2016_pop-und_hg-emissionen_aus_abfallwirtschaftlichen_anlagen.pdf

Table 3-6: Example hourly mercury concentrations after fixed bed filters of two crematoria

#	Crematorium 1 – Line 2 [µg/Nm³, 11 % O_2]	Crematorium 3 [µg/Nm³, 11 % O_2]
1	-	0.170
2	-	0.131
3	70.63	0.128

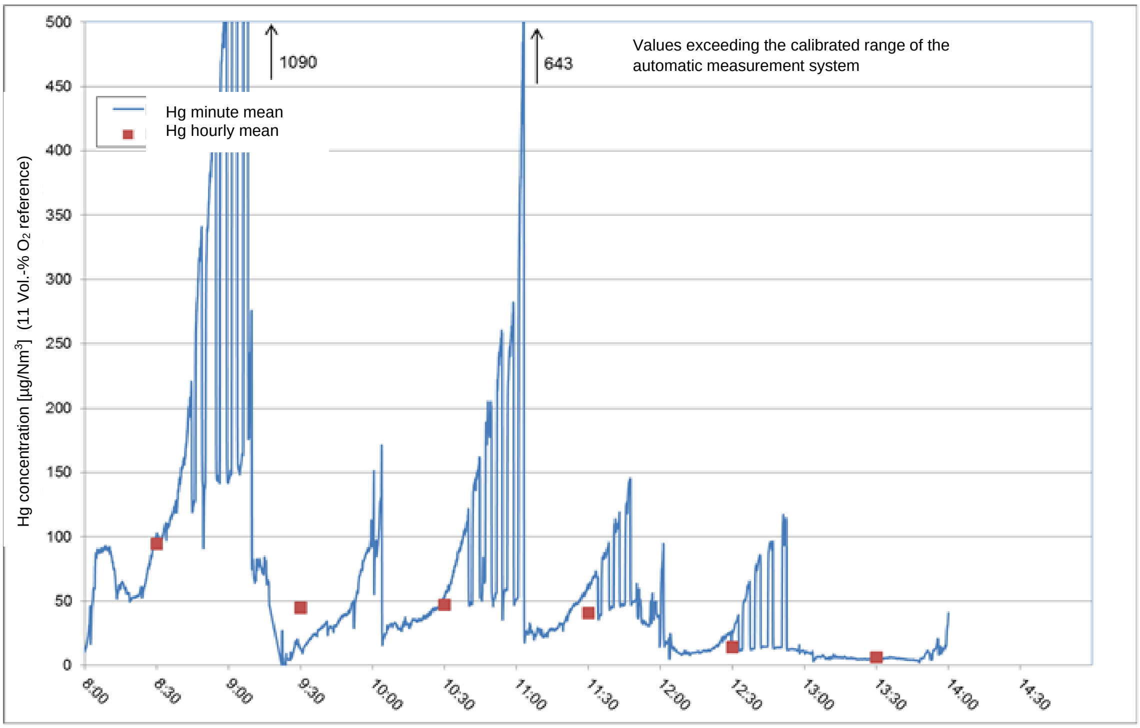
Source: Stöcklein et al. (2016)[59]

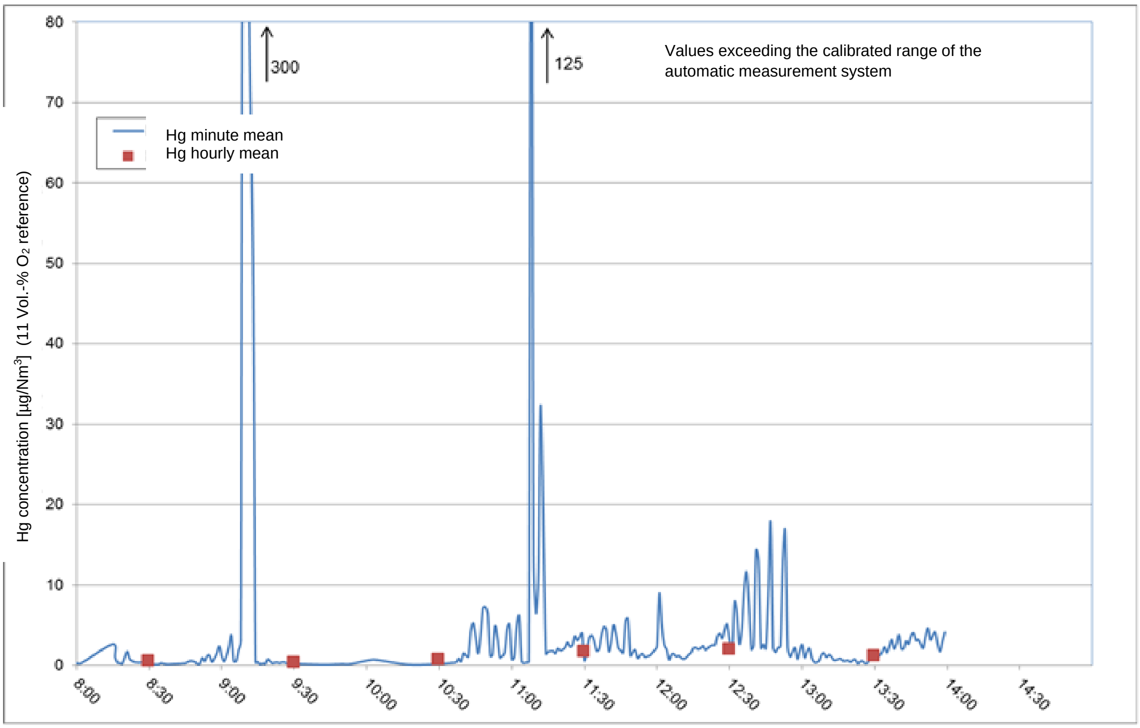
Figure 3-6 shows mercury concentrations measured continuously before and after a fixed bed filter.

From one cremation, mercury emissions of 100 - 500 µg/Nm³ occurred during more than half an hour, with a peak emission of 1090 µg/Nm³ (minute average). The first hourly mean value in the raw gas of ~100 µg/Nm³ was reduced by the fixed bed to a clean gas value below 2 µg/Nm³, and the second hourly mean value of ~50 µg/Nm³ was as well reduced to a value below 2 µg/Nm³ (~98 % removal efficiency).[60] Although mercury peak values were not accurate as above 500 µg/Nm³ were outside the calibrated measuring range, the measurement shows the high ability of the fixed bed filter to reduce total and peak emissions of mercury.

[60] Bittig, M., Haep, S.: Quecksilberemissionen aus Krematorien – Welchen Herausforderungen muss sich die Abgasreinigung stellen? In: Krematorien - Quecksilber und andere Umwelteinflüsse, Schetter, G. (Ed.), ISBN 978-3-936057-62-1, FVB Verlag, Düsseldorf, 2018

Figure 3-6: Mercury raw and clean gas concentration of a crematorium with fixed bed filter showing minute averages (line) and hourly averages (dot) [µg/Nm³, 11 % O_2] Top figure = before fixed bed filter, bottom figure = after fixed bed filter





Source: Bittig/Haep (2018)[61]

[61] Bittig, M., Haep, S.: Quecksilberemissionen aus Krematorien – Welchen Herausforderungen muss sich die Abgasreinigung stellen? In: Krematorien - Quecksilber und andere Umwelteinflüsse, Schetter, G. (Ed.), FVB Verlag, Düsseldorf, 2018

Table 3-7 shows exemplary results of mercury reduction efficiencies measured at the same fixed bed filter, evaluated for mercury concentrations in the raw gas above 20 µg/Nm^3.[62]

Table 3-7: Exemplary mercury reduction efficiency values of a fixed bed filter for raw gas concentrations above 20 µg/Nm^3

Mercury reduction efficiency	Min	Max	Mean	Samples
Fixed bed filter	87.6 %	98.8 %	94.7 %	4

Source: Schetter/Bittig (2020)[63]

If the capacity of the sorbents is exhausted, sorbents need to be replaced. The periods depend mainly on the mercury concentration in the raw gas, on bed size and sorbent characteristics. An indicative range of sorbent consumption is about 0.3 to 0.8 kg/cremation[64] respectively 1,25 to 3,3 cremations per kg activated carbon to achieve mercury emission values below 50 µg/Nm^3.

The Netherlands reported to OSPAR Commission (2016)[65] that the fixed bed filter technique "*has been identified as BAT and results in emission levels of lower than 0.01-0.02 mg/Nm^3*".

Figure 3-7 shows mercury emissions of lines no. 5 and 6 of the crematorium in Kempten (Germany) in relation to load (cremations per kilogram of activated carbon). A consumption of max. 2.2 cremations per kilogram of activated carbon respectively min. 0.45 kg activated carbon per cremation is required to comply with a mercury emission limit of 50 µg/Nm^3. Measurements were applied periodically after 500 cremations to determine the adequate exchange rate of this fixed bed: each 1700 cremations using 750 kg of non-impregnated activated carbon. To avoid desorption, the permit requires continuous temperature monitoring of the flue gas entering the fixed bed, ensuring that 130°C as a 10 min. mean value is not exceeded. [66]

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[62] PCDD/F measurement (6 hour mean values) were 0,0018 ng/Nm^3, 0,0031 ng/Nm^3 and 0,0025 ng/Nm^3

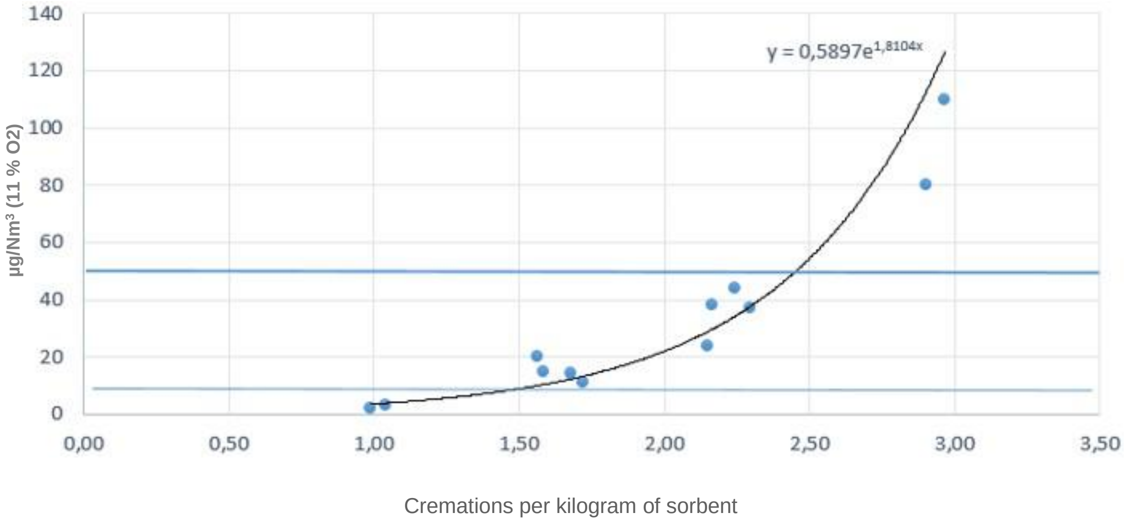
[63] Schetter, G.; Bittig, M.: Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen. Umweltbundesamt (Ed.), UBA-Texte 26/2020.

[64] VDI-Richtlinie 3891:2024 Emission control - Human cremation facilities, Final draft, VDI e.V., Düsseldorf, September 2024

[65] Moxon, R.: Implementation of OSPAR Recommendation 2003/4 on Controlling the Dispersal of Mercury from Crematoria - Second Overview assessment. ISBN: 978-1-911458-05-0, OSPAR Commission, London, 2016

[66] Westermaier, U.: Anlagenüberwachung aus der Sicht einer Kreisverwaltungsbehörde. In: Schetter (Ed.) Krematorium – Klimaschutzziele, Conference 16/17 September 2024, Fachverlag des deutschen Bestattungsgewerbes, ISBN 978-3-93605783-6, Düsseldorf, 2024

Figure 3-7: Mercury emissions [µg/Nm³] related to consumption of activated carbon [cremations/kg] in the fixed bed filter of the crematorium lines 5 and 6 in Kempten/DE



Note: A mercury limit value of 50 µg/Nm³ (hourly mean) must be complied with. PCDD/F analysis on the same measurement days resulted in values between the limit of detection and 0.1 ng/Nm³

Source: Westermaier (2024)[66]

Activated carbon can normally adsorb up to 10-12 % of mercury related to its own weight.[67]

To ensure compliance with 0.2 mg/Nm³, the authority for air quality in the region of Solothurn (Switzerland) requires annually three mercury measurements after fixed bed filters, adding 3 g of mercury to each cremation, and requires also an analysis of the mercury content of the sorbent on defined levels of the filter bed. The resulting exchange rate of the sorbent was each 2000 - 4000 cremations, depending on the type of system.[68]

Dust must be removed periodically from the upstream fabric filter for hazardous waste disposal, same as sorbents of the fixed bed filter at the end of its service life. Usual particle waste is about 0.1 - 0.3 kg per cremation, increased by 0.3 - 0.8 kg of sorbents from the fixed bed filter (VDI 2024)[52].

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[67] Carbon Filter. Sulphuric Acid on the Web. DKL Engineering http://www.sulphuric-acid.com/techmanual/gascleaning/gcl_hg.htm#Carbon%20Filter (22.10.2024)

[68] Mayer, T.: Krematorien: Überwachung Quecksilberabscheidung. Amt für Umwelt Solothurn. Circl’Air - Schweizerische Gesellschaft der Lufthygiene-Fachleute (Ed.), 8 April 2019

3.3.5. Cross-media effects

Fixed bed filters require upstream dust-cleaning with a fabric filter. The fabric filter and the fixed bed filter cause pressure drop, requiring electric energy to achieve sufficient velocity of the flue gas in the stack.

When the sorbent capacity is reached, the material must be disposed in a hazardous waste disposal (e.g. underground mine).

3.3.6. Applicability

Fixed bed filters can be applied in new crematoria and for upgrade of existing crematoria. Upstream systems for cooling, temperature control and dust removal are obligatory as well as a by-pass system.

Fixed bed filters can be combined with all types of crematoria ovens. Usually, one fixed bed filter is connected with the flue gas of one oven.

3.3.7. Economics

According to information from suppliers (2024) and from the Netherlands (2016)[69], investment costs of fixed bed filters are ~250.000 €. The installation of the entire waste gas treatment system including cooling, fabric filter, fixed bed, bypass, insulation and implementation into the Programmable Logic Controller (PLC) are ~€450 000 – 500 000.

Operating costs are associated with refilling of sorbent material and depend on the size of the fixed bed filter (< 1 year up to several years). This includes costs for suction truck rental, waste disposal, sorbent, staff needed to refill the fixed bed container (~2 persons on 2 days using 15 kg buckets). Other operating costs originate from the cooling system, from periodic filter dust disposal and electricity costs for the exhaust fan.

Sorbent costs are about €0.35-0.4 per kg (depending on activated carbon content) plus transport. With e.g. 0.45 kg sorbent consumption per cremation sorbent costs are around €0.16-0.18 per cremation.

3.3.8. Driving force for implementation

Fixed bed filters are mainly applied for removal of PCDD/F and mercury.

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[69] Moxon, R.: Implementation of OSPAR Recommendation 2003/4 on Controlling the Dispersal of Mercury from Crematoria - Second Overview assessment. ISBN: 978-1-911458-05-0, OSPAR Commission, London, 2016

In comparison with sorbent injection systems, fixed bed filters may be selected where the aim of the operator is to obtain a static passive system without parts that may fail operation (no compressors or motors, no moving parts), however requiring more frequent monitoring to avoid mercury overload, and requiring more electricity for the exhaust fan due to higher pressure drop than with sorbent injection.

3.3.9. Example plants

Fixed bed filters are installed in most crematoria in Switzerland, e.g. in Basel, Lucerne, Solothurn, Winterthur, as well as in Germany (in 1999: 15 crematoria, e.g. in Aachen, Gera, Görlitz, Meißen, Potsdam[70], Dachsenhausen[71]), in Mount Jerome (Ireland)[69] and e.g. in the Netherlands[69].

The following description of a fixed bed filter system originates from an installation newly built in 2017 in Basel in Switzerland with three cremation lines.[72] For exemplary measurement data see Table 3-8.

All plant components are configured to meet maximum capacity commitments, even if those are only required occasionally. This is to safely handle coffins with obese bodies that are occasionally delivered to the crematorium and to comply with emission limits also if coffins are made from potentially unsuitable materials or if coffins contain high-energy materials. This could be body packs, unusual amounts of disinfectants or plastics, something that was particularly noticeable at many sites during Covid disease. Although this should all be avoided, the safe handling of such exceptions has been a requirement in the specifications for cremation plants for more than 15 years, irrespective of whether they are for multi-stage or flat-bed cremators, always aiming to suit the individual operating concept of the respective customer as exactly as possible.

In the crematorium of Basel, two lines are designed for 250 kg coffin weight and one line for 450 kg weight, all operated in automatic mode. The flue gas cooling and the abatement systems are designed for gas volumes of 3500 and 4200 Nm^3/h respectively; this relates to heat capacities of 1100 kW and 1400 kW.

The fixed bed filters are equipped with upstream bag filters to remove dust from the cooled flue gas. The fixed bed filters are operated with a lime-coke granulate containing 35 % activated carbon (lines 1+3) respectively 10 % (line 2), with grain sizes of 2-8 mm or 5-8 mm.

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[70] Eigenwillig, S.; Sircar, R.; Tamm, U.; Säuberlich, R.: Stand und Entwicklung bei der Umsetzung der 27. BImSchV. Kulkwitzer Seminar „Kontinuierliche Emissionsmeßtechnik – Krematorien", 24.03.1999

[71] Rhein-Taunus-Krematorium GmbH https://www.rhein-taunus-krematorium.de/nachhaltigkeit/

[72] Clemens, H., IFZW Industrieofen- und Feuerfestbau GmbH & Co. KG, Zwickau, Emails to Ökopol, 4.4./7.4.2025

The maximum volume flow of the fixed bed filter was determined by its flow inlet area and the type of additive used. The abatement efficiency and the lifetime of the filling is determined by the filling level, the type of additive used and the number of cremations.

Table 3-8: Data of the cremators and the fixed bed filter systems at the crematorium in Basel/Switzerland

Cremator type multistage cremator	Line 1	Line 2	Line 3
Cremator case width	2406 mm	2666 mm	2406 mm
Cremator main chamber width	1000 mm	1120 mm	1000 mm
Cremator wall thickness	124 mm	172 mm	124 mm
Cremator coffin weight (max.)	250 kg	450 kg	250 kg
Cremator heat capacity (max.)	1100 kW	1400 kW	1100 kW
Cremations per year	2x 700	600	2x 700
Volume flow (max.)	3500 Nm^3/h	4200 Nm^3/h	3500 Nm^3/h
Fixed bed filter flow inlet area	3.8 m^2	3.8 m^2	3.8 m^2
Fixed bed filter filling level (active)	1.65 m	1.65 m	1.65 m
Fixed bed filter filling level (total)	2.1 m	2.1 m	2.1 m
Sorbent type	35 % activated carbon, 65 % lime hydrate	10 % activated carbon, 90 % lime hydrate	35 % activated carbon, 65 % lime hydrate
Filling level	100 %	100 %	50 % until 2023 then 100 %
Installation costs (air-water-cooling system with heat exchange)	€350,000	No data	€350,000
Installation costs (cyclone and fabric filter with ash extraction, fixed bed filter)	€250,000	No data	€250,000
Mercury emission with 3 g Hg doting (max. of 3 values after ~9000 cremations)	< 0.005 mg/Nm^3 (11% O2)	< 0.005 mg/Nm^3 (11% O2)	< 0.042 mg/Nm^3 (11% O2)
Mercury emission with 3 g Hg doting (max. of 3 values after ~12000 cremations)	< 0.046 mg/Nm^3 (11% O2)	< 0.132 mg/Nm^3 (11% O2)	< 0.006 mg/Nm^3 (11% O2)
Co-benefits	Removal of dioxins, furans and other organic compounds, dust, dust-bound-metals, chloride, fluoride, sulphur dioxides		

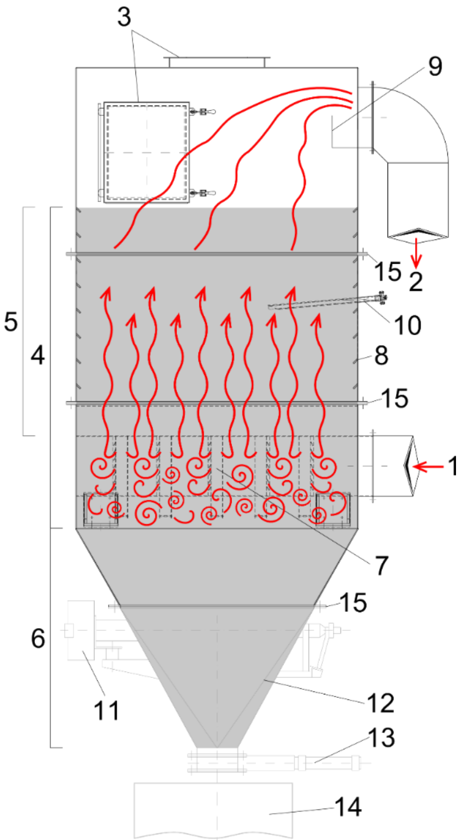
Source: Clemens (2025) [72]

The usual operational load (annual cremations) has an influence on the design of the abatement system. For small cremators and a low number of cremations, e.g. up to about 350 cremations per year, it may be reasonable to operate a fixed bed filter in several stages and without upstream dust removal. For larger plants such a configuration is an economic and ecological burden due to the waste volume produced.

The design of the abatement system is determined by the individual capacity of the cremator and the operation mode of the installed lines. The lifetime of the fixed bed filling is mainly determined by its sorption capacity and by the number of cremations realized. In the interest of sustainability, it is therefore necessary to adapt the system to each respective plant individually. This is also the case for the replacement cycles of the filling, the acceptance measurement after completion of the plant and the frequency of the subsequent measurements.

The crematorium in Basel was designed with sufficient space for the abatement system, therefore three identical filter systems were installed in order to take advantage of identical parts. Figure 3-8 shows the main design features of the installed fixed bed filters.

Figure 3-8: Example of a fixed-bed filter system, crematorium Basel/Switzerland



(1) Raw gas entry (2) Clean gas exit (3) Filling opening (4) Total filling height (5) Active filling height (6) Extraction zone (passive additive) (7) Flue gas distributor (8) Prevention of gas slippage on outside wall (9) Guiding sheet for outlet flow (10) Temperature gauge in filling (11) Vibration motor or knocker (12) Oscillating wall (13) Extraction damper (14) Extraction container or connection of suction vehicle (15) Separation of casing

Source: Clemens (2025) [72]

The raw gas entry (1) leads the flue gas into the additive filling via the flue gas distributor (7). This allows the flue gas to spread as evenly as possible with a low pressure loss. The barrier sheets (8) on the filter walls limit the raw gas slippage to a minimum and allow an even flow of the raw gas through the filling.

The active filling height of the filter (5) determines the lifetime of the additive. The design of the flue gas distributor (7) must ensure that there are no blockages in the area of the distributor.

The fixed-bed filter has extraction devices at the bottom (6) which allow a complete or partial emptying with corresponding auxiliary devices (11, 12, 13, 14). Mostly suction vehicles are used extracting the additive from the top of the filter (3). Partial extraction of additive against the flue gas flow can in principle be very effective but has not become established. For the outlet of the clean flue gas simple measures like guiding sheets for the outlet (9) ensure an optimized additive usage. The main issue here is always to distribute the polluted gas across the filter section as evenly as possible. This ensures a calculable load of the additive that decreases from the incoming gas flow to the clean gas side of the filling.

Annual measurements were carried out, adding 3 g of mercury in each campaign. The first tests in 2020 showed very good results for all three lines. The measurements in 2021 showed significant emissions of cremator 3 in all measurements (see Table 3-9). As expected, the lower filling level in line 3 was associated with a clear efficiency reduction over time; this was confirmed again with the measurements in 2022. In 2022 cremator 2 showed an increase in emissions, as was to be expected due to the lower activated carbon content in the additive (10 % compared to 35 % in lines 1 and 3). Cremator 1 on the other hand showed unchanged low emissions.

In 2023 the additive on cremator 3 was not changed but the filling level was increased to 100 %. The measurement results for cremator 1 and 3 in 2023 were similar. Cremator 2 with a lower carbon content in the additive, again lagged behind lines 1 and 2, which was confirmed by measurements in 2024 (see Table 3-9).

Table 3-9: Hourly mercury concentrations after fixed bed filters of the three lines in Basel in 2021 and 2024

Measure-ment year	Line 1 (starting in 2017) ~1600/a cremations/year 35 % activated carbon 100 % filling level in 2021 and 2024 [µg/Nm³, 11 % O_2] / Reduction efficiency (**)		Line 2 (starting in 2017) ~1600/a cremations/year 10 % activated carbon 100 % filling level in 2021 and 2024 [µg/Nm³, 11 % O_2] / Reduction efficiency (**)		Line 3 (starting in 2017) ~1600/a cremations/year 35 % activated carbon 50 % filling level in 2021 100 % filling level in 2024 [µg/Nm³, 11 % O_2] / Reduction efficiency (**)	
2021-1 (*)	< 0.005	> 99.9%	< 0.005	> 99.9%	< 0.031	> 99.9%
2021-2 (*)	< 0.005	> 99.9%	< 0.005	> 99.9%	< 0.035	> 99.9%
2021-3 (*)	< 0.005	> 99.9%	< 0.005	> 99.9%	< 0.042	> 99.9%
2024-1	< 0.005		< 0.019		< 0.005	
2024-2	< 0.008		< 0.014		< 0.005	
2024-3	< 0.005		< 0.011		< 0.005	
2024-4 (*)	< 0.009	> 99.7%	< 0.132	> 91.3%	< 0.005	> 99.7%
2024-5 (*)	< 0.039	> 98.3%	< 0.062	> 97.7%	< 0.006	> 99.7%
2024-6 (*)	< 0.046	> 98.3%	< 0.077	> 97.3%	< 0.025	> 99.0%

(*) 3 g of mercury added to the cremation (**) based on measured mass flow in relation to 3 g (+ x of body) Hg input

Source: Clemens (2025) [72]

Conclusion of the test series at the Basel reference plant: The manufacturer's information on the life span and the expected number of cremations should be taken into consideration. This information should be verified before the performance guarantee expires, with and without inserting additional mercury. The manufacturer commitments as such are checked in this manner, and at the same time a medium pollutant emission is established which is caused by desorption effects of already separated mercury. The goal is to optimize the use of the filling based on its capacity while ensuring that mercury emissions do not exceed emission limit values. The widespread practice of changing the additive e.g. regularly after 2 years and measuring only after the change of the additive is not recommended.

There is no right or wrong filter size/filling height. The filter dimensions and the filling heights are often determined by the available space – the correct subsequent assessment by measurements of the individual plant is the decisive factor for good economic and ecological results. Small filter systems need more frequent replacements of small amounts of additives. Large systems need less frequent replacement, but larger amounts of additives. Systems with bad design, however, will be identified by regular measurement and replaced accordingly.

Whilst additives with 10 % activated carbon content have a lower purchase cost than additives with 35 % of activated carbon, the shorter service life leads to higher disposal costs so that the total cost for the operator is higher. The lines with 35 % activated carbon content show very good results even after five years of operation.

3.4. Sorbent injection ("co-flow filter", "entrained-flow sorption process", "dry sorbent injection")

3.4.1. Short description

Sorbent material is injected into the flue gas. Usually activated carbon or activated coke is used, mixed with inert sorbents. Mercury and other gaseous substances are bound on the outer and inner surface of the sorbent. The loaded particles are separated from the flue gas in a fabric filter. In contrast to wet or semi-wet injection of sorbents, the system is also called "dry sorbent injection". As the reaction of the sorbent with pollutants partly takes place in the gas flow, it is also called "entrained-flow sorption process" or "co-flow filter". The technique is mentioned in the OSPAR Recommendation 2003/4.[73]

3.4.2. Technical description

The technique of dry sorbent injection consists of two key components: sorbent injection into the flue gas and a fabric filter. For the injection of the sorbent material different techniques were developed and applied. In the simplest version sorbent material is introduced into the flue gas flow via a spiral conveyor. A more effective way is injection of sorbents with compressed air to achieve better contact of sorbents with mercury and other pollutants.

After injecting the sorbent material into the flue gas flow, it is of high importance to achieve a good mixture and contact of the sorbent with the pollutants in the flue gas. Mixing is usually done in a reactor, for example in a cyclone or a multi-cyclone. To improve sorbent distribution, multi-stage, non-clogging nozzles can be used for injection, installed over the entire duct cross section, or counter-flow swirl nozzles. Effectivity depends on turbulence, temperature and contact time.

Subsequently, the flue gas reaches the fabric filter. Dust particles including sorbents build up a layer on the surface of the fabric filter ("filter cake"), allowing in the layer additional reactions of the sorbent with mercury and other pollutants.

Dust including sorbents loaded with pollutants are separated from the filter by periodical cleaning using a reverse flow of compressed air. The particles are collected in the hopper of the filter and fall into containers (drums) installed below.

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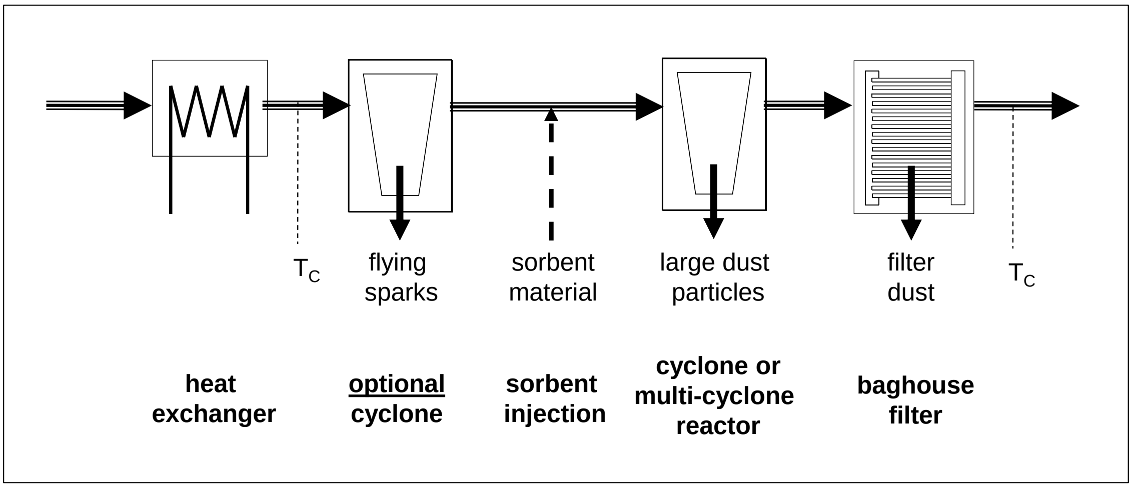
[73] OSPAR Recommendation 2003/4 on Controlling the Dispersal of Mercury from Crematoria, OSPAR Commission, London, 2003

The containers are equipped with inliners and closed for final hazardous waste disposal (e.g. in underground mines).

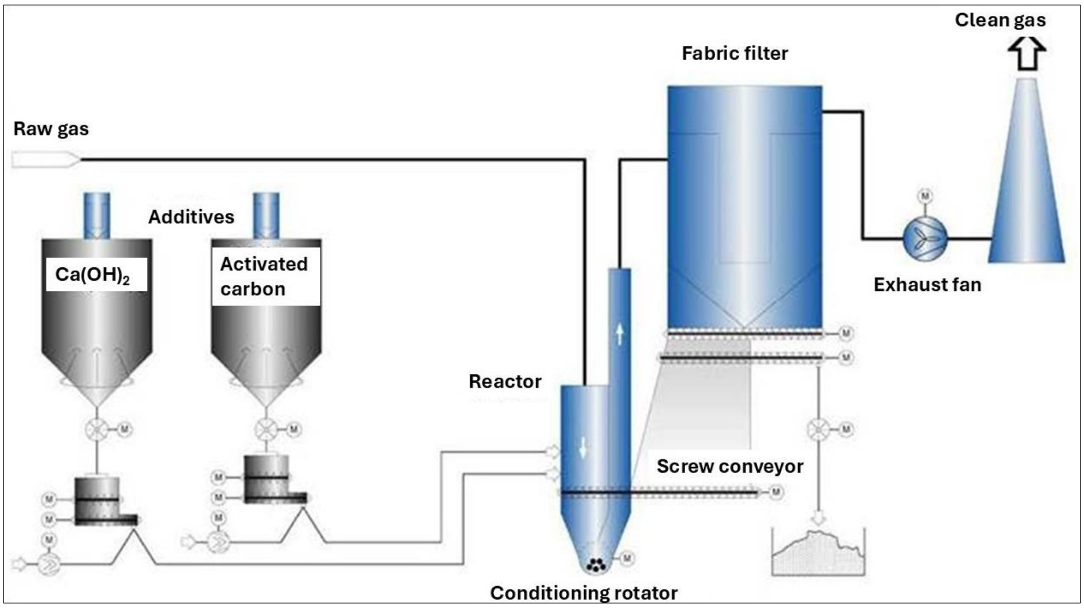
Figure 3-9: Scheme of flue gas treatment system with sorbent injection



Source: Own diagram by Schetter

A variation of the sorbent injection system is the so-called "conditioning rotor-recycle process" as shown in Figure 3-10. This system consists of sorbent injection into the reactor, a reactor with a conditioning rotor filled with heavy balls, a baghouse filter and a partial sorbent-recirculation with integrated conditioning. Compared to the basic dry sorbent injection described above, the rotor reactor ensures an intensive contact and reaction area for the physical and chemical conversions between mercury and other harmful substances with the sorbent material. Due to over-stoichiometric injection of sorbents the separated filter dust contains a high portion of unreacted sorbents. By partial particle-recirculation the sorbent consumption as well as the quantity of residual products can be reduced.

Figure 3-10: Scheme of sorbent injection with conditioning rotor-recycle



Source: Margraf (2018) [74]

Figure 3-11: Photo of sorbent injection with conditioning rotor-recycle

Source: Schetter (2016) [75]

Storage, handling and injection of sorbents consisting of 100 % activated carbon implies a risk of self-ignition (> 250°C) and explosion (flue gas with > 12 % oxygen content). Therefore, the flue gas requires cooling before sorbent injection. Activated carbon is usually mixed with inert material (typically lime hydrate).

The sorbent material is usually delivered in big bags (e.g. 300 - 400 kg) or casks (e.g. 120 l or 220 l).

3.4.3. Achieved environmental benefits

Sorbent injection systems reduce organic compounds (e.g. PCDD/F) and mercury efficiently. If lime hydrate is used, also acidic pollutants are reduced like sulphur oxides, chloride and fluoride. The sorbent injection system can achieve high removal rates also in case of mercury peaks. However, efficiency depends on the injected amount of sorbent, its distribution and its contact time with the flue

[74] Margraf, R.: Verfahrenstechnische Lösungen zur Quecksilberabscheidung. In: Schetter G.: Krematorium. Quecksilber und andere Umwelteinflüsse. Fachverlag des Deutschen Bestattungswesens, Düsseldorf, 2018

[75] Schetter, G.: Langzeituntersuchungen zu Emissions- und Schadstoffminderungen in Krematorien durch veränderte energieeffiziente Betriebsweisen. Deutsche Bundesstiftung Umwelt (Ed.), Osnabrück, 2016

gas, the flue gas temperature and the thickness of the cake built-up on the fabric filter.

3.4.4. Operational data

Table 3-10 shows operational data of sorbent injection.

Table 3-10: Operational data of sorbent injection

Parameter	Typical values	Source
Temperature of fixed bed	~ 100 - 150°C	VDI 3891 (2024) [76]
Pressure drop	~ 3 - 5 hPa	VDI 3891 (2024) [76]
Raw gas velocity in layer on the fabric filter	~ 0.02 m/s	VDI 3891 (2024) [76]
Mean sorbent consumption	~ 0.2 - 1 kg/cremation	VDI 3891 (2024) [76]
	0.6 kg daily pre-coating and 0.6 kg per cremation, using 80 % sodium bicarbonate and 20 % activated carbon (AC) = 0.15 kg AC for pre-coating and 0.15 kg AC per cremation	Interview with provider of sorbent injection technique (2024), mainly providing in the United Kingdom (compliance with 50 µg/Nm^3) and Sweden, achieving levels < 30 µg/Nm^3

Mercury removal rates are difficult to determine due to:

- Extreme variation of mercury concentration in the raw gas (calibrated measurement range of continuous measurement equipment is often exceeded).
- Limited possibilities to fulfil standard measurement conditions for raw gas measurement (generally met in straight flue gas duct sections with an undisturbed inlet section of five hydraulic diameters upstream and an undisturbed outlet section of two hydraulic diameters downstream of the measuring cross-section and a distance to the end of the flue gas duct of at least five hydraulic diameters).
- Limited representativity of a) the mercury input of cremations during the measurement,
  b) the injected mass and type of sorbent at the time of measurement (may be varied).

The mercury removal efficiency depends on:

- amount of injected sorbent,

[76] VDI-Richtlinie 3891:2024 Emission control - Human cremation facilities, Final draft, VDI e.V., Düsseldorf, September 2024

- sorbent characteristics (grain size determining the outer surface, pore volume determining the inner surface, impregnation leading to chemisorption),
- contact time (mixing intensity of flue gas with sorbents and reaction time in the flow and in the layer of the fabric filter),
- flue gas temperature,
- competing flue gas components (e.g. sulphur dioxide).

An indicative range of sorbent consumption is about 0.2 to 1.0 kg/cremation (VDI 2024)[76]. To ensure that the injection rate is sufficient to reduce mercury peak emissions, periodic measurement (e.g. yearly, potentially with mercury added during measurement) should be applied, together with monitoring of purchased sorbent per number of cremations. One provider reported that measurement results were all below 30 µg/Nm3 (hourly average) after daily pre-coating of the fabric filter before starting cremations, executing just one filter cleaning at the end of the day, and using 0.6 kg/cremation with a mixture containing 20 % activated carbon, hence 0.15 kg/cremation (no measurement data was provided).

Table 3-11 shows exemplary results of mercury reduction efficiencies measured after sorbent injection with simple injection or with conditioning rotor-recycle injection systems. For all measurements, the mercury concentration in the raw gas was above 20 µg/Nm^3.

Table 3-11: Exemplary mercury reduction efficiency of sorbent injection for raw gas concentration > 20 µg/Nm^3

Mercury reduction efficiency	Min	Max	Mean	Samples
Simple sorbent injection	77.6 %	98.0 %	85.2 %	4
Sorbent injection with conditioning rotor-cycle	89.7 %	99.6 %	94.5 %	7

Source: Schetter/Bittig (2020)[77]

Raw gas concentrations on the first measurement day at the conditioning rotor cycle injection resulted in hourly mean values of 1540/189/103 µg/Nm^3. Despite the high mercury input, clean gas values were 5.2/64/10 µg/Nm^3. Although mercury peak values above 500 µg/Nm^3 were not accurate as outside the calibrated measuring range, the measurement shows the high ability of the conditioning rotor cycle sorbent injection system to reduce total and peak emissions. Sorbent consumption and type of sorbent were not documented.[77]

Raw gas concentrations at the simple injection system resulted in hourly mean values of 7 - 818 µg/Nm^3 and clean gas values of 4 - 107 µg/Nm^3 (no

[77] Schetter, G.; Bittig, M.: Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen. Umweltbundesamt (Ed.), Texte 26, Dessau-Roßlau, 2020

documentation of single values). Reduction efficiencies varied from 55 – 98 % (including raw gas concentrations below 20 µg/Nm^3).[77]

Table 3-12 shows exemplary results of mercury reduction efficiencies measured after sorbent injection with a simple injection system and 300g sorbent injection per cremation (70% lime hydrate, 30% sulphur-doted activated carbon). For each of the three measurements, 3g of mercury was added to the cremation. The total mercury input is not known due to different amalgam fillings of the bodies.

Table 3-12: Exemplary hourly mercury input/output (standardised, 11 % O_2) and reduction efficiency of sorbent injection using sulphur-doted activated carbon when adding 3 g of mercury in the crematorium of Lucerne

#	Raw gas [g/h]	Clean gas [g/h]	Reduction efficiency	Clean gas [µg/Nm^3]
1	3 + x	0.055	> 98%	46
2	3 + x	0.092	> 97%	95
3	3 + x	0.022	> 99%	24

Source: Burg (2025) [78]

However, if sorbent rate is low, sorbent injection can also lead to high emission values. Three measurements after a sorbent injection system in Italy showed clean gas values of 5/80/300 mg/Nm^3 (11 % O_2). Each of the three measurements was conducted during about two hours per cremation. Sorbent rate was not documented, it was just mentioned that the type of sorbent was “activated carbon with lime or with sodium bicarbonate” (Santasioro et al. 2006).[79] Emission values after sorbent injection are also documented by OSPAR (2003) with a range of 0.001 - 0.1 mg/Nm^3 [80], but without specifying type of sorbent and injection rate per cremation.

In contrast where a lot of sorbents are injected, it is shown that very low mercury emissions result: Takaoka et al. (2021)[81] conducted 39 measurements of 43 – 75 min per cremation documenting raw gas and clean gas values. For sorbent injection a 9:1 mixture of lime and activated carbon was used. The BET value of the activated carbon was 120 m^2/g. “The mixture was pre-injected at a rate of 35 kg/h for 1.5 h before each cremation. After six cremations, the dust and reacted and unreacted products were removed by pulse jet cleaning.” This results in

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[78] Burg, H., Ruppmann Verbrennungsanlagen GmbH Stuttgart, Email to Ökopol, 25.2.2025

[79] Santasioro, A.; Settimo, G.; Dell’Andrea, E.: Mercury emission from crematoria. Annali dell'Istituto Superiore di Sanità 2006 | Vol. 42, no. 3: 369-373

[80] OSPAR Recommendation 2003/4 on Controlling the Dispersal of Mercury from Crematoria, OSPAR Commission, London, 2003

[81] Takaokaa, M.; Chenga, Y.; Oshitaa, K.; Watanabec, T.; Eguchi, S.: Mercury removal from the flue gases of crematoria via pre-injectionof lime and activated carbon into a fabric filter. Process Safety and Environmental Protection 148, 2021

~3500 g activated carbon injection per cremation. Clean gas mean values per cremation were all below 1 µg/Nm^3, measured with continuous emission monitoring (measuring range: 0.1 to 1000 µg/m^3). Raw gas values varied between 2.0 - 159 µg/Nm^3, with six values above 30 µg/Nm^3 (44.2/50.6/54.2/81.6/156/159). The average of all 39 raw gas measurements was 22.0 µg/Nm^3, and 17 µg/Nm^3 referring to 12 % O_2. With this huge sorbent rate, efficiencies were in most cases 97.0 – 99.9 %, except five cases with 87.5 - 95.7 % where low mercury input concentrations of 2.9 – 7.7 µg/Nm^3 were measured.

Table 3-13 and Table 3-14 show exemplary measurement results in raw gas and clean gas from crematoria applying sorbent injection with the conditioning rotor cycle system. In both installations, raw gas sampling was done on a point not fully complying with standard measurement conditions; however, the flow profile was considered as appropriate for the measurements. Raw gas measurement was stated to be in many cases near the limit of detection of 0.01 mg/Nm^3. The study did not aim at determining mercury reduction efficiency. Due to the measurement uncertainty of the raw gas measurement, in particular for low concentrations, a reduction efficiency may only be derived from measurement no. 7 (81 %) in Table 3-13 and no. 5 (88 %) in Table 3-14.

Table 3-13: Exemplary hourly mercury concentration (raw/clean gas, standardised, 11 % O_2) of sorbent injection using the first generation of conditioning rotor cycle systems in the crematorium of Berlin

#	Raw gas [mg/Nm^3]	Clean gas [mg/Nm^3]
1	0.01	0.010
2	0.01	0.009
3	0.17	0.015
4	0.02	0.019
5	0.03	0.044
6	0.02	0.016
7	1.71	0.321
8	0.14	0.019
9	0.19	0.077
10	0.08	0.032

Note: Raw gas measurement was done on a sampling point not complying with standard conditions. "Raw gas measurement was in many cases near the limit of detection of 0.01 mg/Nm^3". No information on type of sorbent and sorbent injection rate.

Source: Schetter (2016)[82]

[82] Schetter, G.: Langzeituntersuchungen zu Emissions- und Schadstoffminderungen in Krematorien durch veränderte energieeffiziente Betriebsweisen. Deutsche Bundesstiftung Umwelt (Ed.), 2016

Table 3-14: Exemplary hourly mercury concentration (raw/clean gas, standardised, 11 % O_2) of sorbent injection using the first generation of conditioning rotor cycle systems in the crematorium of Munich

#	Raw gas [mg/Nm³]	Clean gas [mg/Nm³]
1	0.01	0.01
2	0.01	0.01
3	0.01	0.01
4	0.01	0.01
5	1.62	0.20
6	0.04	0.01
7	0.39	0.11
8	0.04	0.01
9	0.06	0.01
10	0.39	0.02
11	0.01	0.01
12	0.01	0.01
13	0.01	0.01
14	0.01	0.01
15	0.02	0.01
16	0.14	0.01
17	0.03	0.01
18	0.02	0.02
19	0.05	0.01
20	0.04	0.01

Note: Raw gas measurement was done on a sampling point not complying with standard conditions. "Raw gas measurement was in many cases near the limit of detection of 0.01 mg/Nm³". No information on type of sorbent and on sorbent injection rate.

Source: Schetter (2016)[82]

Dust must be removed periodically from the fabric filter for hazardous waste disposal. Usual particle waste is about 0.1 - 0.3 kg per cremation, increased by 0.2 - 1 kg from sorbent injection (VDI 2024)[76].

3.4.5. Cross-media effects

Sorbent injection systems require fabric filters which lead to pressure drop, requiring electric energy to achieve sufficient velocity of the flue gas.

The particles removed from the fabric filter must be disposed in a hazardous waste disposal (e.g. underground mine).

3.4.6. Applicability

Sorbent injection systems can be applied in new crematoria and for upgrade of existing crematoria. Temperature control and by-pass systems are obligatory.

Sorbent injection systems can be combined with all types of crematoria ovens. Usually, one sorbent injection systems is connected with the waste gas of one oven.

3.4.7. Economics

According to providers, investment costs of sorbent injection systems (consisting of a dosing silo and a pneumatic injection) in combination with a cooling system and a fabric filter are about €200,000-250,000 (conditioning rotor-recycle process at the upper and of the range). The installation of the entire system with cooling, sorbent injection, fabric filter, insulation and implementation into Programmable Logic Controller (PLC) are ~€450,000-500,000.

Operational costs include costs for sorbents, waste disposal, electricity (for compressed air or mechanical injection as well as for fans) and regular system maintenance.

Sorbent costs are about €0.35-0.5 per kg plus transport (the upper end e.g. for 70% lime hydrate and 30% activated carbon doted with sulphur). With e.g. 0.6kg injection per cremation and additional pre-coating of the filter each morning with 0.6kg, about 0.65kg sorbent is consumed per cremation with associated sorbent costs of about €0.23-0.35 per cremation. With 0.3kg sorbent injection per cremation and without pre-coating in the morning, associated costs are €0.11-0.15 per cremation.

3.4.8. Driving force for implementation

Sorbent injection systems are mainly applied for removal of PCDD/F and mercury.

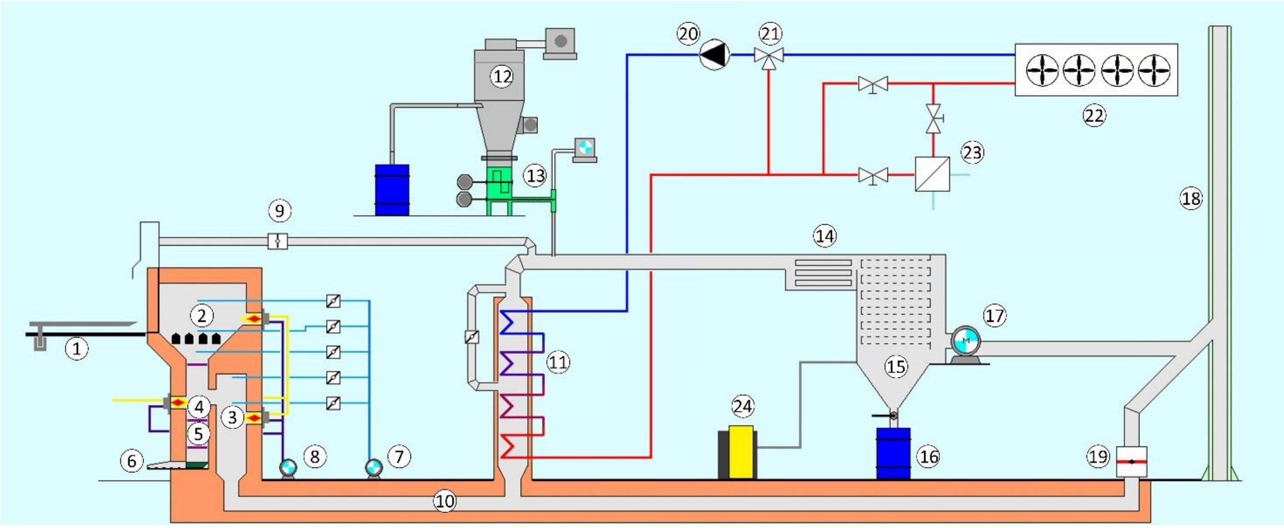
In comparison with fixed bed filters, sorbent injection systems may be selected where the aim of the operator is to ensure mercury reduction without the requirement for regular, e.g. half-year mercury monitoring to detect break-through of fixed bed filter systems.

3.4.9. Example plants

There are many sorbent injection systems installed in crematoria, e.g. in Austria, Denmark, Germany, Norway, Spain, Sweden, and in the Netherlands.[83]

The following description of a sorbent injection system originates from an installation in 2022 at an existing cremator and cooling system in the crematorium of Lucerne in Switzerland. For measurement data see Table 3-12 in Section 3.4.4.

Figure 3-12: Example of a sorbent injection system, crematorium Lucerne/Switzerland



(1) Coffin insertion (2) Main combustion chamber (3) Post combustion chamber (4) Ash burnout zone (5) Ash cooling chamber (6) Ash extraction (7) Combustion air supply (8) Burner air supply (9) Fume extraction (10) Underfloor duct (11) Heat exchanger with bypass (12) Sorbent silo (13) Sorbent dosing (14) Multicyclone (15) Fabric filter (16) Dust removal (17) Flue gas ventilator (18) Stack (19) Bypass valve (20) Cooling water pump (21) 3-way valve (22) Air cooling (23) Heat recovery (24) Compressed air production

Source: Burg (2025) [84]

[83] 51 systems in Germany in 1999 according to Eigenwillig, S.; Sircar, R.; Tamm, U.; Säuberlich, R.: Stand und Entwicklung bei der Umsetzung der 27. BImSchV. Kontinuierliche Emissionsmeßtechnik – Krematorien, Kulkwitzer Seminar, 24.03.1999

[84] Burg, H., Ruppmann Verbrennungsanlagen GmbH Stuttgart, Email to Ökopol, 25.2.2025

Table 3-15: Data of the sorbent injection system at the crematorium in Lucerne/Switzerland

Cremator type	Multi-stage cremator
Cremations per year	2000
Volume flow (mean)	2000 Nm3/h
Volume flow (max.)	2800 Nm3/h
Fabric filter surface	84 m^2
Temperature during normal operation	140°C
Temperature for bypass operation	170°C
Sorbent type	30 % activated carbon (sulphur-doted), 70 % lime hydrate
Sorbent injection per cremation	300 g
Activated carbon consumption per cremation (sulphur doted)	30 g
Sorbent consumption per year	600 kg/a
Sorbent costs per kilogram	€0.5 /kg
Sorbent costs per cremation	€0.15
Sorbent costs per year	€300/a
Installation costs (silo, pneumatic injection, fabric filter)	€150,000
Mercury emission with 3 g Hg doting (max. of 3 values)	95 µg/Nm^3 (11 % O_2); 0,09 g/h
Mercury reduction efficiency with 3 g Hg doting (lowest of 3 values)	> 97 %
Mercury reduction efficiency with 3 g Hg doting (mean of 3 values)	> 98 %
Co-benefits	Removal of dioxins, furans and other organic compounds, dust, dust-bound-metals, chloride, fluoride, sulphur dioxides

Source: Burg (2025) [84]

3.5. Sorbent Polymer Composite (emerging technique)

3.5.1. Short description

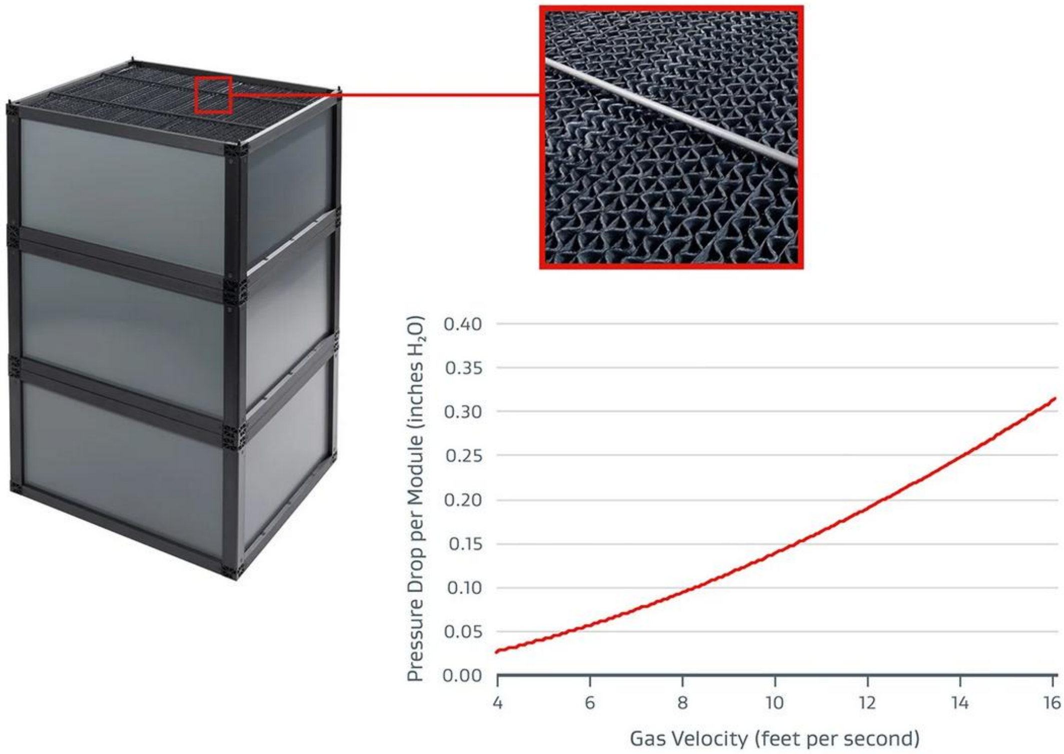
An expanded PTFE polymer matrix contains sorbents, catalysts and sulfur. Oxidized and elemental mercury can penetrate the matrix. Both are bound chemically and physically by the sorbent.

3.5.2. Technical description

The Sorbent Polymer Composite (SPC) technique is a modular system of an expanded polytetrafluorethylene (PTFE) polymer matrix. The modules with a dimension of 0.6 m x 0.6 m x 0.3 m are installed in several layers, depending on the required reduction efficiency. The structure of the system is similar to a honeycomb catalyst.[85]

Carbon-containing sorbents, catalysts and sulphur are integrated in the expanded PTFE polymer matrix. Oxidised and elemental mercury can penetrate the matrix and are bound both chemically and physically by the sorbent. In case SO_2 is present in the flue gas, it is converted to liquid sulphuric acid. As the matrix is hydrophobic, sulphuric acid cannot penetrate and rolls off on the surface.

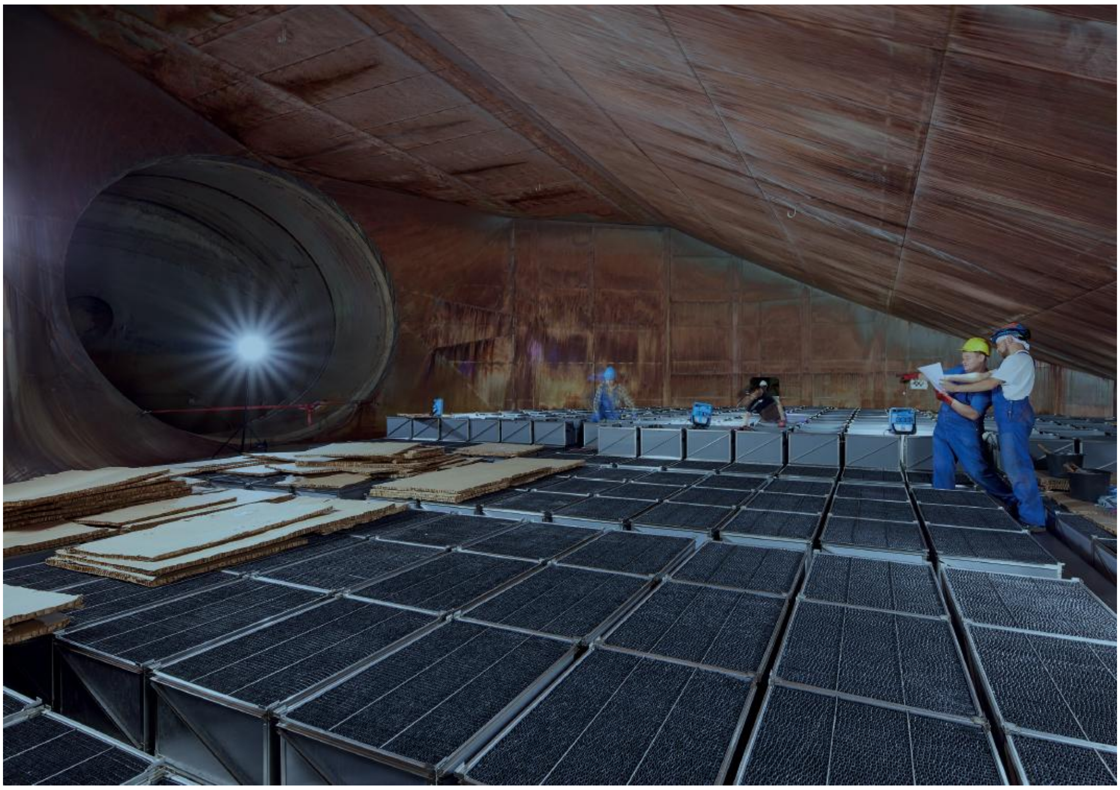
Figure 3-13: Sorbent Polymer Catalyst (SPC) picture and pressure drop depending on gas velocity



Source: GORE 2024

[85] Dehoust, G.; Gebhardt, P.; Tebert, C.; Köser, H.: Quecksilberemissionen aus industriellen Quellen - Status Quo und Perspektiven. Abschlussbericht – Teil 2: Quecksilberminderungs-techniken und Überführung von Quecksilber in Senken. UBA Texte 68, Umweltbundesamt (Ed.), Dessau-Roßlau, 2021

Figure 3-14: Installation of SPC on the wet scrubber system of the lignite power plant of Chemnitz



Source: GORE 2023

3.5.3. Achieved environmental benefits

Elemental and oxidized mercury as well as sulfur dioxide are removed by the SPC technique. Until reaching the standing time of the system, mercury reduction is reliably achieved without loss of reduction efficiency.

3.5.4. Operational data

The operating temperature is about 65° - 80°C. Water is required for periodic cleaning and humidification of the modules.

The mercury reduction efficiency depends on the number of layers installed. With two layers, a mean of 43 % reduction efficiency was achieved in a lignite power plant. After 290 days of operation in that lignite power plant with a mean raw gas concentration of about 17 µg/Nm^3 and mercury reduction to a level of about 7 µg/Nm^3, 3 % of the sorption capacity was exhausted; after four years

16 % was achieved. The expected service life is more than 10 years.[86] Information about sorption capacity during peak emissions is not known.

For crematoria, a mercury removal efficiency of about 90-97 % is calculated, depending on the number of layers installed. (GORE 2025) [87]

3.5.5. Cross-media effects

The production of PTFE material is associated with emissions of persistent per- and polyfluoroalkyl substances (PFAS) (ECHA 2023).[88]

When the sorption capacity of the SPC modules is reached, the modules must be disposed as hazardous waste.

3.5.6. Applicability

Sorbent Polymer Composite systems can be applied in new crematoria and for upgrade of existing crematoria. Temperature control is obligatory.

The SPC modules can only be used effectively in a humid environment. Space requirement is an issue, depending on the number of layers to be installed. Modules can be installed in several subsequent side-by-side towers.

In crematoria, SPC modules could be applied as additional system for mercury abatement downstream of a catalytic fabric filter system, installed mainly for dust and PCDD/F removal. The flue gas outlet of the catalytic fabric filter (~200°C) would require humidification and cooling to about 65°-80°C.

3.5.7. Economics

Economics of the technique depend on the targeted mercury reduction efficiency. The following data show exemplary cost calculations to achieve either 90 % reduction efficiency or 97 % reduction efficiency, assuming a flue gas volume of 4000 m^3/h. The system requires flue gas cooling to achieve 65°C.

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[86] Petzold, O.; Schauer, P.: Kohlekraftwerke mit weniger Quecksilber, Umweltmagazin, Bd. 3 Nr. 1-2, 2023. https://www.gore.de/system/files/2023-03/Artikel_UmweltMagazin_Kohlekraft_mit_weniger_Quecksilber_Feb2023.pdf

[87] W.L. GORE & Associates GmbH, Email to Ökopol, 25.5.2025

[88] ECHA (2023): Annex XV Restriction Report – Proposal for a Restriction - Per- and poly-fluoroalkyl substances (PFASs). Submitters: BAuA/DE, RIVM/NL, KEMI/SE, Norwegian Environment Agency/NO, EPA/DK. European Chemicals Agency (ECHA), Helsinki, 2023 https://echa.europa.eu/documents/10162/1c480180-ece9-1bdd-1eb8-0f3f8e7c0c49

Operational costs include electricity costs for ventilation(additional pressure drop is low), costs for periodic spray cleaning of the modules with water, for acidic water disposal, and for modules disposal when the system is loaded.

Table 3-16: Cost calculation for mercury removal with Sorbent Polymer Composite technique

Volume flow	4000 m^3/h	4000 m^3/h
Volume flow (dry, normal conditions)	2429 Nm^3/h	2429 Nm^3/h
Flue gas temperature	65°C	65°C
Pressure drop	872 Pa	1260 Pa
Cremation duration	30 min	30 min
Hg peak input per cremation	2 g	2 g
Hg peak concentration (normal conditions, 10 % O_2)	1647 µg/Nm3	1647 µg/Nm3
Hg peak emission (normal conditions, 10 % O_2)	165 µg/Nm3	50 µg/Nm3
Hg removal efficiency	90 %	97 %
Installation costs equipment	120 000 – 135 000 €	170 000 – 250 000 €
Mean Hg input per cremation	0.5 g	0.5 g
Cremations per year	2000	2000
Hg absorption per module per cremation	~23 %	~23 %
Hg load of first module after four years	0,95 kg	0,95 kg
SPC modules standing time if first three modules are exchanged with last three modules after 2 years	8 years	8 years
Module costs per cremation	7.5 €	10.5 €
Additional costs	Acidic water disposal	Acidic water disposal
Co-benefit	SO_2 reduction	SO_2 reduction

Source: GORE (2025)[87]

Compared with e.g. sorbent injection systems, SPC modules are associated with significantly higher investment costs per cremation. The system does not provide the same co-benefits as sorbent injection or fixed-bed systems (e.g. additional costs arise for removal systems for dust and organic compounds like dioxins/furans). Operating costs are significantly lower than for systems using activated carbon, and disposed waste is significantly reduced. Disposal costs only occur at the end of the lifetime.

3.5.8. Driving force for implementation

SPC modules are selective for the removal of mercury and sulphur dioxides. For this reason, the system would rather be implemented in crematoria with existing systems for removal of dust and organic compounds like PCDD/F (i.e. after catalytic fabric filters).

The system does not require maintenance. The only operation during the standing time of the modules is water spraying for cleaning and removal of acidic water from the bottom of the system. The system allows safe operation, which is a benefit where unskilled staff is contracted, as it does not require handling of sorbent material nor handling of contaminated waste. No measures are needed to avoid explosion risk.

3.5.9. Example plants

The technique is used for mercury reduction from flue gases on industrial scale in sewage sludge incinerators as well as in coal- and lignite-fired power plants. Reference plants can be found in the USA, in Japan and in Europe. Example plants are the lignite power plants in Melnik (Czech Republic) and Chemnitz (Germany). The technique is not used in crematoria yet.[89]

3.6. Selenium filter (emerging technique)

3.6.1. Short description

The selenium filter removes mercury from flue gas by converting selenious acid into red amorphous selenium, reacting with gaseous mercury to form mercury(II) selenide.

3.6.2. Technical description

The selenium filter is a fixed bed filter with a large surface area to achieve good contact with mercury in the flue gas. A porous inert material similar to a catalyst is impregnated with red amorphous selenium. The impregnation is achieved by drying selenious acid solution in the presence of sulfur dioxide to precipitate red amorphous selenium.

The red amorphous selenium reacts with the mercury in the gas to form mercury(II)selenide (HgSe). The contact time in the filter is about 1-3 seconds. The pressure drop is about 600 Pa for a one-stage filter with a three-second retention time.

The filter remains effective until the level of mercury in the filter reaches 10–15%. The filter is then treated to recover the mercury and regenerate the selenium.

[89] Dehoust, G.; Gebhardt, P.; Tebert, C.; Köser, H.: Quecksilberemissionen aus industriellen Quellen - Status Quo und Perspektiven. Abschlussbericht – Teil 2: Quecksilberminderungstechniken und Überführung von Quecksilber in Senken. UBA Texte 68, Umweltbundesamt (Ed.), Dessau-Roßlau, 2021

The filter operates at temperatures up to 110 °C with water-vapor-saturated gases. The vapor pressure of mercury at temperatures of 0-100 °C is very low compared to HgSe (melting point: 1000°C). The vapor pressure of amorphous selenium is also very low at these temperatures (melting point 221°C), and selenium losses are minor. Condensation inside the filters, however, should be avoided.[90, 91]

3.6.3. Achieved environmental benefits

Elemental and oxidized mercury are removed from the flue gas and fixed as HgSe. Regeneration requires a mercury reduction system that does not lead to mercury emissions from evaporation.

3.6.4. Operational data

There is no data available as no installation in crematoria were identified.

The technique is used for cleaning of sulphur-containing waste gases upstream of sulphuric acid plants in the non-ferrous metals industry (roasting of ores containing e.g. copper, gold, lead, zinc). Table 3-17 shows reduction efficiencies of the copper/lead/zinc smelter in Rönnskär (Sweden) with a gas flow of 80,000 Nm^3/h (no reference oxygen content provided).

Table 3-17 Exemplary mercury reduction efficiency data of a selenium filter

	Before filter [µg/Nm^3]	After filter [µg/Nm^3]	Reduction efficiency	Source
High inlet	6000	< 50	99 %	Hultbom (2003)[91]
High inlet	1008	48	95 %	BREF NFM (2014)[92]
Low inlet	42	12	71 %	

[90] Guidance on Best Available Techniques and Best Available Environmental Practices, Secretariat of the Minamata Convention on Mercury, UNEP, Geneva, 2019 https://minamataconvention.org/en/resources/guidance-best-available-techniques-and-best-environmental-practices#nav-paragraph-en

[91] Hultbom, K. B.: Industrially proven methods for mercury removal from gases. EPD congress, The Minerals, Metals & Materials Society (TMS), 1 January 2003

[92] Cusano, G.; Rodrigo Gonzalo, M.; Farrell, F.; Remus, R.; Roudier, S.; Delgado Sancho, L.: Best Available Techniques (BAT) Reference Document for the Non-Ferrous Metals Industries, Joint Research Centre, ISBN 978-92-79-69655-8, European Commission, Seville/Spain, 2017 https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC107041_NFM_bref2017.pdf

Similar to the non-ferrous metals industry, the selenium filter was implemented in geothermal plants for gases with very high mercury content (1.2 kg per hour, i.e. about 1000 times higher than in crematoria). Average efficiencies were reported with 90 - 95%. However, efficiency of the selenium filter decreased from 94.9 % and 80.6 % in 2012 to 48.4/85.3/74.5 % in 2013. "The high values of total mercury at the Bagnore 3 plant - which testify to a low abatement capacity - are to be attributed - according to ENEL - to a defective supply of selenium sorbent, which has led to a decrease in the abatement efficiency of this pollutant, which historically has always recorded values above 90%.[93]

3.6.5. Cross-media effects

Mercury selenide may be emitted. The substance is fatal if swallowed (H300), fatal in contact with skin (H310) and fatal if inhaled (H330). It may cause damage to organs through prolonged or repeated exposure (H373). It is very toxic to aquatic life with long lasting effects (H410).[94]

3.6.6. Applicability

The selenium filter can only be used effectively in a humid environment.

In crematoria, selenium filters could be applied as an additional system for mercury abatement downstream of a catalytic fabric filter system, installed mainly for dust and PCDD/F removal. The flue gas outlet of the catalytic fabric filter (~200°C)[95] would require humidification and cooling to a maximum of 110°C. The system supplier (Metso) informed in 2024 that selenium filters for small flue gas volumes are not available.

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[93] Impianto di Abbattimento Mercurio e Idrogeno Solforato (AMIS). ARPAT - Agenzia regionale per la protezione ambientale della Toscana. https://www.arpat.toscana.it/temi-ambientali/sistemi-produttivi/impianti-di-produzione-di-energia/geotermia/controllo-delle-emissioni/abbattimento-delle-emissioni-delle-centrali-geotermiche (24.10.2024)

[94] Information on chemicals. European Chemicals Agency (ECHA), 21 October 2024. https://echa.europa.eu/de/information-on-chemicals

[95] Schetter, G.; Bittig, M.: Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen. Umweltbundesamt (Ed.), Texte 26, Dessau-Roßlau, 2020.

3.6.7. Economics

Industry sources report indicative investment costs for a selenium filter with 200,000 m^3/h capacity of about €3 million plus 70 tons of selenium at a price of €35,000 per tonne, resulting in another €2.45 million. If scale down would be proportionate, resulting costs for 4,000 m^3/h capacity would require an investment of €60,000 plus approximately €50,000 for 1.4 tons of selenium. Additional associated costs comprise investment costs for cooling and for removal of organic compounds like dioxins and furans because the system does not have co-benefits.

Operational costs include costs for humidification as well as for selenium recovery and mercury disposal when the filter is loaded.

3.6.8. Driving force for implementation

Selenium filters are selective for the removal of mercury. For this reason, the system would rather be implemented in crematoria with existing systems for removal of dust and organic compounds like PCDD/F (i.e. after catalytic fabric filters).

The system does not require maintenance. The only operation is water spraying for humidification and removal of the water from the bottom of the system.

3.6.9. Example plants

No crematoria reference plants. Selenium filters are applied in ferrous and non-ferrous metals industries as well as for cleaning of gases from geothermal plants in Italy.[96] At least six plants are operating in the non-ferrous metals industry, e.g. in Rönskar (UNEP 2019)[90], and there are applications for flue gas cleaning in geothermal plants in Italy, e.g. in Bagnore.[96, 93]

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[96] Mercury reduction is feasible. NORDEN - Nordic Council of Ministers, ISBN 978-92-893-2079-5, Copenhagen, 2010 https://norden.diva-portal.org/smash/get/diva2:701717/FULLTEXT01.pdf

3.7. Guidance on applicability, effectiveness and costs of techniques and guidance for Member States

This section provides additional guidance to decisionmakers on the basis of three aspects of mercury abatement techniques:

- Applicability
- Environmental performance
- Costs

3.7.1. Applicability/technical viability

The applicability of a technique depends on:

- The availability of suppliers (and related maintenance service) at the location of the operator
- Preconditions/pre-requisites for the technique to be used (e.g. flue gas temperature, humidity, dust content) which require additional upstream installations of e.g. for cooling, humidification and dust cleaning. This is associated with a higher complexity of the installation and increased costs.
- Additional complexity of systems may also have implications on complexity of maintenance and the need for more skilled/expert staff, with associated costs.
- Space restrictions are always a local issue when upgrading existing installations. Flue gas treatment systems (including cooling and dust cleaning) require about the same space as a simple installation with an oven not using flue gas treatment.

For identified BAT and emerging techniques, guidance with respect to applicability, including availability of suppliers, requirements including space and temperature/need for additional systems, and maintenance is shown below.

Table 3-18: Assessment of applicability of mercury reduction techniques

System	Applicability	Complexity and need for additional systems	Maintenance
Fixed bed	Several EU providers available	Requires bypass, upstream cooling and upstream dust cleaning	Passive system (No moving parts that may fail), fully automatic Regular system revision, dust disposal, filter bed disposal after year(s)
Sorbent injection	Several EU providers available	Includes dust cleaning. Requires upstream cooling.	Regular system revision, dust and loaded sorbent disposal
Sorbent injection with rotor-cycle	One provider in the EU at the time of the drafting of this guidance	Includes dust cleaning. Requires upstream cooling.	Regular system revision, dust and loaded sorbent disposal
Sorbent Polymer Composite	One provider in the EU at the time of the drafting of this guidance.	Requires upstream system for removal of dust and organic compounds like PCDD/F (e.g. catalytic filter). Requires upstream cooling.	Acidic water disposal, mercury disposal
Selenium filter	One provider in the EU at the time of the drafting of this guidance, not providing for small flue gas volumes.	Requires upstream system for removal of dust and organic compounds like PCDD/F (e.g. catalytic filter). Requires upstream cooling. Requires service for recovery of the selenium filter.	Recovery of the filter, mercury disposal

Fixed bed filters are produced by several suppliers in the EU. They require additional systems including upstream cooling and upstream dust cleaning. As they are a passive system without compressors or moving parts, they are less prone to failure and without the need for skilled technical maintenance. With that said, the replacement of sorbent will be required after about one to several years (depending on dimension and load) which requires either the use of a specialist suction truck or manual labour. Additionally, the mercury emission of the bed must be frequently monitored (at least once a year).

Sorbent injection is also available from several suppliers in the EU, albeit with only one supplier offering sorbent injection with rotor-cycle. Sorbent injection also requires upstream cooling, however filtration of dust and organic compounds is included as co-benefit of the system. There are fewer monitoring requirements however, the system requires more technical maintenance unlike the passive fixed bed systems. This is particularly the case for the systems with rotor cycle, having more moving parts. The system continuously produces waste of loaded sorbent to be disposed.

Sorbent Polymer Composite is an emerging technique (for use in the cremation sector). The modules are offered by only one provider. The technique is most applicable for crematoria that have existing filter systems for removal of dust and organic compounds. It is a simple passive system without compressors or moving parts and therefore less prone to failure and without the need for skilled technical maintenance. The filter has a long-term constant removal rate and therefore requires less monitoring.

Selenium filters are an emerging technique (for use in the cremation sector). The filters are offered by only one provider but not for small volume flows. The technique is most applicable for crematoria that have existing filter systems for removal of dust and organic compounds. The filter has a long-term constant removal rate and therefore requires less monitoring.

3.7.2. Environmental performance

The environmental performance of a technique regarding the reduction of mercury is difficult to assess for the following reasons:

- The same system can vary, e.g. regarding the type of sorbent used (activated carbon content in the sorbent), the dosing rate of injected sorbents respectively the size/height of a bed filter.
- It requires representative data which implies a relatively high number of measurements as the input of mercury varies significantly depending on the amalgam fillings of a body.
- It requires raw gas and clean gas measurement under certain conditions at the sampling point (undisturbed and uniform flow of the flue gas), often not given in existing installations, in particular not for raw gas.
- It needs to take into account varying flue gas volumes and associated variations of the oxygen content in the flue gas. To avoid mixing effects, results need to be converted to values referring to a standard oxygen content (usually 11 %).
- It needs measurement equipment that can cope with dust in the raw gas measurement and (in case of continuous monitoring) sufficient calibrated range to provide valid results for both, low and peak emissions. The monitoring equipment needs to produce reliable results, both for oxidised and elemental mercury. Dust-bound mercury also needs to be analysed although low concentrations are expected after fabric filters. Due to significant variations of the flue gas volume, an isokinetic sampling should be done.

Table 3-19 shows, for each technique, a summary regarding Hg efficiency including specific data on abatement and other environmental impacts. A general assessment of Hg efficiency is provided as well as specific data on abatement efficiency achieved in crematoria. Information on co-benefits of the technique as well as on consumables (reactants, electricity) is also presented.

Table 3-19: Environmental performance of mercury reduction techniques

System	Hg efficiency	Mercury efficiency data	Co-Benefit	Reactants	Electricity consumption
Fixed bed with upstream cooling and fabric filter	High if sufficient bed length and bed changed on time	Crematorium (DE): Min: 87.6%, max: 98.8 %, mean out of 4 samples: 94.7 % FI: 99%*[97]	Organic compounds like PCDD/F. Acidic compounds if adequate sorbents are used	Activated carbon or coke. Lime or sodium bicarbonate to abate acidic compounds.	For fan due to pressure drop
Sorbent injection with upstream cooling and downstream fabric filter	High if sufficient sorbent is injected	Crematorium (DE): Min: 77.6 %, max: 98.0 %, mean out of 4 samples: 85.2 % Crematorium (CH): > 98 % (3 samples with 3 g Hg doting, 300 g sorbent per cremation injected)	Dust, organic compounds like PCDD/F. Acidic compounds if adequate sorbents are used	Activated carbon or coke. Lime or sodium bicarbonate to abate acidic compounds.	For fan due to pressure drop, for compressor for sorbent injection
Sorbent injection with rotor-cycle with upstream cooling and down-stream fabric filter	High if sufficient sorbent is injected	Crematorium (DE): Min: 89.7 %, max. 99.6 %, mean out of 7 samples: 94.5 %	Dust, organic compounds like PCDD/F. Acidic compounds if adequate sorbents are used	Activated carbon or coke. Lime or sodium bicarbonate to abate acidic compounds.	For fan due to pressure drop, for motor for sorbent injection
Sorbent Polymer Composite (SPC) with upstream cooling and catalytic fabric filter	High if sufficient modules are installed	Lignite-fired power plant (DE): 43 % (mean of 290 days) applying two SPC layers. 90 – 97 % assumed for crematoria, depending on the number of layers	SO_2	PTFE polymer carbon catalysts	For fan due to pressure drop and for water spraying
Selenium filter with upstream cooling and catalytic fabric filter	Not sufficient data to evaluate whether Hg from cremation is reduced efficiently	NF metal plant (SE): 71 % for 42 µg/Nm³ Hg input 95 % for 1008 µg/Nm³ Hg input 99 % for 6000 µg/Nm³ Hg input Geothermal plant IT: 94.9/80.6/48.4/ 85.3/74.5 % for high Hg input	None	Porous inert material impregnated with red amorphous selenium	For fan due to pressure drop and water spraying

[97] According to information shared by Member State

Based on a few data where raw gas and clean gas was measured, sorbent injection with rotor-cycles showed similar abatement efficiencies as fixed bed filters (94.5% and 94.7% mercury abatement, respectively). Sorbent injection without rotor-cycle had slightly lower abatement (85%), but no injection rate was reported. For an injection rate of 300g per cremation, 97% abatement was shown when 3g of mercury was added to the cremation. Reduction efficiency of Sorbent Polymer Composite systems depends on the size of the system; up to 90 – 97% efficiency is expected for crematoria. Selenium filter does not have demonstrated efficiency in crematoria, however, achieves up to 99% efficiency for high mercury loads in non-ferrous metal plants.

Sorbent injection and fixed bed filters provide abatement of organic compounds such as PCCD/F. Sorbent injection additionally provides dust abatement. Selenium filters only abate mercury. SPC systems provide co-benefits in abatement of SO_2 (however usually less relevant in crematoria). All techniques require electricity for fans. Sorbent injection requires additional energy for compressors/motors.

3.7.3. Costs

Information on costs of techniques that are shortlisted on the basis of applicability is shown in Table 3-20.

Table 3-20: Cost data for mercury abatement systems shortlisted on the basis of applicability

Technique	CAPEX	OPEX
Fixed bed filter	**€250,000**[98] for fixed bed filter alone **€450,000 – 500,000** for complete system including cooling, fabric filter, fixed-bed, bypass, insulation and implementation into PLC	**€5,000/year**[99] Operating costs associated with: • refilling of sorbent material, which will include either the use of a suction truck or manual carrying of sorbent in buckets (~4 man days)- Frequency varies with size of filter • Electricity costs (exhaust fan and cooling system) • Dust filter replacement Additional costs arise from waste disposal for filter dust and exhausted sorbents.

98 OSPAR, 2016, confirmed more recently from supplier interviews (2024)

99 OSPAR, 2016

Technique	CAPEX	OPEX
Sorbent injection ("co-flow filter")	**€200,000- 250,000** for sorbent injection system including dosing silo and pneumatic injection. Upper end of the range for rotor-cycle **€450,000-500,000** for complete system including cooling (conditioning rotor-recycle process more expensive and thus represents the upper end of the range), fabric filter, sorbent injection, insulation and implementation into PLC	**€5,000/year** Operating costs are assumed to be the same as for fixed bed filter, i.e. including cost for sorbent, electricity, etc. While there is not the need for suction truck rental and staff for manual re-filling as with the fixed bed filters, there is a greater need for supervision / maintenance. Higher energy costs associated with compressed air / mechanical injection may be compensated by less energy costs associated with the exhaust fan due less pressure drop as with fixed bed filters. Additional costs arise from waste disposal for filter dust mixed with loaded sorbents.
Sorbent Polymer Catalyst	**€230,000** for SPC system with 4000 m3/h capacity. These costs are estimated regarding the equipment for installation of modules and water spray system (€117,000 only SPC) **€500,000** for complete system including cooling and catalytic fabric filter, insulation and implementation into PLC	Operating costs are required for cooling and exchange of SPC modules when absorption capacity is reached. Costs are estimated with about €15 per cremation (90 % reduction efficiency) Additional costs arise from waste disposal for acidic water and SPC modules.
Selenium filter	**€110,000** for selenium filter with 4000 m3/h capacity and 1.4t of selenium required. These costs are estimated scaled down from larger industrial installations (€3m for 200,000m3/h capacity). **€500,000** for complete system including cooling and catalytic fabric filter, insulation and implementation into PLC	Operating costs are required for cooling and recovery of selenium filter material. Quantitative data on operational costs is not available. Additional costs arise from waste disposal for mercury resulting from selenium recovery.

The investment and operating costs for the two most common / best performing techniques, fixed bed filters and sorbent injection system, are broadly the same. For selenium filters, there is a lack of data on costs. Assumptions had to be made on the basis of scaling down costs from selenium filters used in larger industrial installations. As such, while the investment costs appear lower for a selenium filter, the system requires addition installation of a catalytic filter system as otherwise PCDD/F would not be reduced. There is less certainty on the exact costs in reality.

It is important to emphasise that investment costs for mercury abatement encompass not just the filtration technique, but the wider system required, in particular the necessary cooling system. The requirement for cooling systems to be installed to facilitate mercury abatement systems represent a significant additional cost.

- The investment costs for implementation of a **direct cooling system** are in the region of **€30,000.**
- Investment costs for **indirect cooling** such as through the implementation of a heat exchanger in combination with a closed water cycle are €100,000 – 120,000 for installation of heat exchanger including tube bundles and €40,000 – 50,000 for a closed water cycle, i.e. total costs of **€140,000-170,000**
- In addition to cooling, the technique must be **incorporated into the Programmable Logic Controller (PLC)** with an estimated cost of **€10,000 – 20,000**

Due to the size and structure of techniques, retrofitting techniques in existing sites will usually lead to significant reconstruction costs which will be highly site specific. Additional site-specific costs or barriers may be present which hinder implementing BAT for mercury abatement. Such instances include when crematoria are located in old heritage/protected buildings which would prevent or drastically increase the costs of reconstruction necessary to implement techniques. However, rebuilds of old crematoria usually lead to significant increase of energy efficiency by using newer cremators.

BAT for mercury abatement as indicated above are in the region of €500,000 for a complete system (including waste gas cooling) with additional annual costs also associated. As such, it will be important for competent authorities to consider the size/ annual cremations of a given site as well as the location in terms of proximity to sensitive receptors when considering the installation of techniques at specific installations.

4. Member State legislation

This section presents available information on current Member State legislation with respect to mercury emissions from crematoria. The impact assessment in support of the revision of the Mercury Regulation[44] identified national-level legislation addressing mercury emissions from crematoria through a stakeholder survey and a literature review. It found regulations with ranges from 0.05 – 0.2 mg/Nm^3 in seven Member States, and four Member States with local/regional regulation in place.

In an effort to update the findings from the 2023 impact assessment a preliminary email was sent to Member State authorities on 10 September 2024, asking for information on regulations for mercury emissions from crematoria and abatement techniques applied in crematoria. The deadline for this request was 22 October 2024. Three responses were received (the Netherlands, Ireland and Finland).

Table 4-1: EU Member State regulations on mercury emissions from crematoria

Member State	Regulation of crematoria mercury emissions
AT	No regulation identified, although some sources indicate an emissions limit value (ELV) of 0.1 mg/Nm^3 (dry gas, 11% O_2) was implemented[100].
BE	ELVs of 0.2 mg/Nm^3 and 0.1 mg/Nm^3 (dry gas, 11% O_2) in effect in Flanders and Brussels, respectively[101]. In Wallonia, there is an emission limit value of 0.05 mg/Nm^3 as a daily average for mercury (at 1013 hPa, 273 K, 11% O_2, on dry gas) with a monitoring frequency of at least every 3 years.
BG	No regulation identified.
CY	No regulation identified.
CZ	No regulation identified.
DE	No legislation, but Germany has adopted guidance on BAT in human cremation installations, which indicates that when dust filters and/or sorbents are utilised, typical mercury emissions range between 0.1 and 50 µg/m^3 (fixed bed filter or sorbent injection).
DK	Legislation BEK nr 2079 af 15/11/2021[102] sets a mercury ELV of 0.1 mg/Nm^3 (dry gas, 11% O_2) for crematoria with an annual capacity of over 400 cremations. Flue gas must be tested once yearly for mercury.
EE	No regulation identified.
EL	No regulation identified.
ES	No regulation identified.

100 Eurocrematoria (2008) Cremation and respect for the environment. https://www.funeralnatural.net/sites/default/files/articulo/archivo/ecn_manifesto_definitive.pdf

101 Deloitte, Ineris, Wood (2020), Assessment of the feasibility of phasing-out dental amalgam – Final report https://circabc.europa.eu/sd/a/4fd46a0f-54aa-48c6-8483-288ad3c1c281/Dental%20Amalgam%20feasbility%20study%20-%20Final%20Report.pdf

102 Retsinformation (2021). BEK nr 2079 af 15/11/2021. https://www.retsinformation.dk/eli/lta/2021/2079

Member State	Regulation of crematoria mercury emissions
FI	Finland largely follows and adopted the HELCOM recommendations - crematoria with a capacity exceeding 500 cremations per year implement BAT to comply with an ELV of 0.1 mg/Nm^3 (11 % O_2).
FR	The Arrêté du 28 janvier 2010 relatif à la hauteur de la cheminée des crématoriums et aux quantités maximales de polluants contenus dans les gaz rejetés à l'atmosphère[103] sets an ELV of 0.2 mg/Nm^3 (dry gas, 11% O_2).
HR	Regulation NN 87/2017[104] establishes an ELV of 0.05 mg/Nm^3.
HU	No regulation identified.
IE	No national-level regulation in place. Crematoria emissions are regulated locally through the permitting system, where ELVs are specified on an installation-by-installation basis.
IT	No national regulation in effect. Regional rules generally establish an hourly average emission limit value of 0.05 mg/Nm^3 (dry gas,11% O_2).[105]
LT	Order No. D1-357[106] sets an ELV of 0.1 mg/Nm^3.
LU	No regulation identified.
LV	No regulation identified.
MT	No regulation identified.
NL	Article 4.119 of the Environmental Management Activities Decree[107] sets an ELV of 0.05 mg/Nm^3 (dry gas,11% O_2).
PL	No regulation identified.
PT	No regulation identified.
RO	No regulation identified.
SE	All crematoria require environmental permits, either from national or local authorities depending on operating capacity. Permits specify best practices and BAT. An emission limit value of 0.08 mg/Nm^3 (dry gas,11% O_2) is applied.[108]
SI	No regulation identified.
SK	No regulation identified.

103 Légifrance (2010) Arrêté du 28 janvier 2010 relatif à la hauteur de la cheminée des crématoriums et aux quantités maximales de polluants contenus dans les gaz rejetés à l'atmosphère. https://www.legifrance.gouv.fr/loda/id/JORFTEXT000021837100/

104 Narodne Novine (2017) Uredba o graničnim vrijednostima emisija onečišćujućih tvari u zrak iz nepokretnih izvora. https://narodne-novine.nn.hr/clanci/sluzbeni/2017_08_87_2073.html

105 SEFIT (2024) https://www.sefit.org/sefit/include/docum/files/Sefit-Ispra_Studio%20Cremazione_2024.04.10.zip

106 Valstybės žinios (2008). Dėl Aplinkosaugos reikalavimų kremavimo įmonėms aprašo patvirtinimo. https://www.e-tar.lt/portal/legalAct.html?documentId=TAR.09B74C209D3A

107 Overheid.nl (2022) Activiteitenbesluit milieubeheer. https://wetten.overheid.nl/BWBR0022762/2022-07-01/

108 ECN (2018) https://dfweurope.com/wp-content/uploads/2018/01/ECN-chart-comparing-atmospheric-emissions-of-crematoria.pdf

5. Monitoring practices, techniques and standards

5.1. Techniques and standards

There are various methods used within Europe for measuring and monitoring mercury emissions in exhaust gases. Two methods are used widely throughout Europe, these relate to discontinuous and continuous measurements using isokinetic sampling and automatic measuring. The two methods are in accordance with the relevant European standards. A third method using sorbent traps is in accordance with a European pre-standard (validation outstanding). National regulations outline if mercury emissions are to be measured continuously or discontinuously.

Discontinuous measurements are usually based on to the European standard EN 13211:2001, manual reference method for the determination of the mass concentration of mercury in exhaust gases from ducts and chimneys[109]. Total mercury concentrations are most commonly determined by using isokinetic flow sampling from exhaust gases at suitable measuring points followed by oxidation and absorption of mercury in an aqueous solution. Mercury is quantified in the solution by atomic absorption spectroscopy (AAS). Results from this type of measurement require laboratory analysis. The usual measurement duration is one hour (one cremation). The validated method for measuring range of 1 – 500 µg/Nm^3 (mean value during the sampling period) documents a limit of quantification (LOQ) of about 1 µg/Nm^3.

Continuous mercury measurements adhere to the European standard EN 14884:2022[110], stationary source emissions determination of total mercury: automated measuring systems. The most widely used method is also isokinetic flow sampling from exhaust gas followed by chemical reduction of oxidized to elemental mercury. The latter is quantified by atomic absorption spectroscopy (AAS). EN 14884:2022 sets out suitable measuring points and samples must be collected in accordance with these standards. Results from continuous monitoring using automatic measuring equipment is output in half-hour averages, daily averages and annual averages. EN 14884:2022 also sets out the requirements of the three-stage quality assurance necessary. This includes suitability testing, functional testing and device calibration as well as the associated timeframes for testing and frequency of device testing. Using cold vapor AAS, the achievable limit of quantification may be as low as 0.06 µg/Nm^3.

[109] European Committee for Standardisation (CEN). EN 13211:2001 Air quality – Stationary source emissions – Manual method of determination of the concentration of total mercury.

[110] European Committee for Standardisation (CEN). EN 14884:2022.

Sorbent traps are an automatic measuring method to monitor total vapour phase mercury emissions in flue gas. Sorbent traps can be used for both short-term (periodic) and long-term (continuous) monitoring purposes. These monitoring systems involve continuous repetitive in-flue sampling using paired sorbent traps requiring laboratory analysis of the time-integrated samples. The duration of the measurements is between 30 minutes and 4 weeks. The CEN/TS 17286:2019[111] standard document establishes performance benchmarks for sorbent trap monitoring systems. The method can only be applied where mercury in dust emissions is low (as is usually the case in crematoria).

ISO 54009:2024[112] is the international standard published for stationary source emissions – chemical absorption method for sampling and determining mercury species in flue gas. This standard describes a method for sampling and determining mercury species in flue gas passing through ducts or chimney stacks, and is suitable for flue gases with high dust content. This method applies to sampling gaseous elemental mercury (Hg0), gaseous oxidized mercury (Hg2+), particulate-bound mercury (HgP) and total mercury (HgT) in the flue gas from stationary sources.

Finally, the standard EN 14884:2022[113] specifies requirements for the calibration and validation, ongoing quality assurance during operation and annual surveillance test of automated measuring systems for monitoring mercury emissions. This standard relates to EC directive 200/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste, and directive 94/67/EC incineration of hazardous waste.

5.2. Interpreting data / challenges (guidance)

Due to the high variations of mercury input resulting from different amount of amalgam fillings, mercury measurements in crematoria can result in varied data. Results may neither be representative nor reliable to check the performance of the waste gas abatement system.

This challenge can only be solved by three approaches:

- Apply long-term measurements using automatic measurements systems according to EN 14884 or

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[111] European Committee for Standardisation (CEN)/TS 17286:2019 Stationary source emissions – Mercury monitoring using sorbent traps

[112] International Organisation for Standardisation (ISO). ISO 5409:2024 Stationary source emissions — Chemical absorption method for sampling and determining mercury species in flue gas

[113] EN 14884:2022 Stationary source emissions – determination of total mercury – automated measuring systems

- Apply long-term measurement using automatic measurement with sorbent trap systems according to CEN/TS 17286:2019 or
- Add mercury to the cremation combined with short-term measurements according to EN 13211:2001

Automatic measurement systems according to EN 14884 imply high investment costs (> €100,000) and high maintenance costs for functionality tests and calibrations. At the same time, calibration for the entire range of mercury emission values from crematoria is not possible. The system is not suitable to determine correct hourly mean values where high peak emissions of more than 1000 µg/Nm^3 occur. [114] Although the peaks only last for a few minutes, the total emissions of mercury per cremation is likely to be underestimated. The system can provide an overview on the variation of mercury emitted from each cremation as well as mean values of days or weeks. Results of the measurement are available immediately. Due to the high costs, the system may be used for research but is not appropriate for regular performance checks in crematoria.

Automatic measurement systems using sorbent traps according to CEN/TS 17286:2019 can cope with high peak emissions (overload of a sorbent is detected in a break-through section). Sampling is done with paired decides, which can be used for quality assurance. Sampling over a long period of time better ensures representative data than periodic measurements. However, the system only provides a mean value of the mercury output over the sampling time, e.g. one week or up to four weeks. Results of the measurement will only be available after laboratory analysis, hence after at least several days. To obtain representative results it is recommended to annually undertake two samplings of two weeks each to obtain representative results. The results serve for evaluation whether a low mean mercury emission concentration is achieved (e.g. < 50 µg/Nm^3). Costs of the measurement are higher than for conventional measurements according to EN 13211 because the measurement company has to install and deinstall the sampling system on several days, and costs for consumables are higher than for chemicals used for EN 13211 (costs are ~€130 for each of the two paired traps while chemical costs are <€10 per measurement).

Addition of mercury combined with short-term measurements according to EN 13211 can check whether the abatement system achieves a high reduction rate for mercury peaks. While many cremations may have low mercury input, some peak input may occur. Fixed bed filters and sorbent injection systems use a static mass of activated carbon for adsorption and do not vary the mass according to the mercury input. Mercury addition to the cremation can support finding the best type of sorbent and sorbent injection rate. Three measurements dosed with 3 g of mercury are considered to be sufficient to check whether a defined reduction

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[114] Zunzer, U.: Quecksilbermessung im Roh- und Reingas in Krematorien. In: Schetter G.: Krematorium. Quecksilber und andere Umwelteinflüsse. Fachverlag des Deutschen Bestattungswesens, Düsseldorf, 2018.

efficiency (or an emission limit value) is achieved with a sorbent injection system. For fixed bed filters, annual measurement using 3g of mercury addition is recommended to check whether the activated carbon has reached its absorption capacity or whether priority flows have been formed in the bed which reduce the performance.

6. Appendix 1: Detailed information on origin and fate of mercury during cremation

6.1. Sources of mercury input in crematoria

In cremation, several sources may contribute to the overall input of mercury to the incineration system. These comprise of

- Dental amalgam fillings
- Human body (except dental amalgam fillings)
- Coffin, decoration and burial objects
- Fuel (not relevant for electric cremators)

The average mercury content of the human body not containing amalgam fillings was estimated to be in the order of 14 mg [115] (other data: 3.3 mg[116], 0.0096-120 mg[117]) with liver and kidney as body parts with a high mercury concentration. The coffin, its decoration and other embedded objects have a mercury content of about 0.2 mg. If natural gas is the main energy source and its consumption per cremation is 1.7 to 60 m^3 [118], at a maximum of 10 ng Hg/m^3 in processed and cleaned natural gas[119], the mercury input from fuel would be in the order of 0.02 to 0.6 mg.

The main source of mercury in cremation is the presence of amalgam in the deceased's dental fillings. Several estimations of the mean mercury inventory per deceased are available (see Table 6-1). They strongly depend on the national situation (dental health and level of amalgam use) as well as the period when the estimations were done (due to improving dental health care and decreasing amalgam use over time). Reports from Japan and Germany provide lower estimates at 31.7 and 80 to 200 mg, but considerably higher values were derived for the USA and Canada (1200mg to as high as 5600 mg in one region). It should

[115] Ohle A. et al. (2021) Quecksilber- und Feinstaubemissionen von Krematorien: Ein Überblick. Chem. Ing. Tech. 93, No. 3, p. 390–411;

[116] Takaoka M. et al. (2010) Mercury emission from crematories in Japan. Atmos. Chem. Phys. 10, p. 3665-3671. Actually, an estimate from 1977.

[117] Reindl J. (2015) Summary of References on Mercury Emissions from Crematoria. https://no2crematory.wordpress.com/mercury/

[118] Schetter (2022) Ein Krematorium energieeffizient betreiben (Teil 1). Friedhofskultur (2022/10), p. 20-25. Gas usage per cremation strongly depends on the number of cremations per day as well as the temperature maintained in after-burn chamber

[119] Chalkidis et al. (2019) Mercury in natural gas streams: A review of materials and processes for abatement and remediation. J. Hazardous Mater. 121036

be kept in mind that individual deceased may have a much higher inventory (several 1000 mg).

Table 6-1 Estimated mercury content of deceased

Country	Mercury content (medium) [mg]	Year of publication (data source may be older)
UK	3000	1990[120]
USA	1500	1995[121]
Switzerland	2000	1995[122]
Denmark	4000	2001[123]
USA /New Jersey	800-5600	2002[124]
UK	1920	2004[125]
Italy	36-2140	2006[126]
Japan	31,7	2010[116]
USA/ Minnesota	2300	2015[127]
North America + Europe	1000-4000	2017[128]
Europe	1490 (*)	2023[129]

[120] Mills (1990) Mercury and crematorium chimneys, Nature, 346, p. 615.

[121] US EPA (1997) Locating and estimating air emissions from sources of mercury and mercury compounds. EPA-454/R-97-012

[122] Matter-Grütter C. et al. Schweiz. Monatsschr. Zahnmed. 1995, 105 (8), 1023–1028. In: Ohle et al. [115]

[123] Christensen S. L. et al. (2004) Mass flow analyses of mercury2001. Environmental Project Nr. 917 2004. Miljøprojekt. Danish Environmental Protection Agency. https://www2.mst.dk/udgiv/publications/2004/87-7614-287-6/pdf/87-7614-288-4.pdf

[124] DiFrancesco D. T. et al. (2002) New Jersey Mercury Task Force Report. Volume III. Sources of Mercury in New Jersey. https://dep.nj.gov/wp-content/uploads/dsr/mercury-task-force-volume-3.pdf

[125] Passant, N.R. (2004): Review of emission factors for mercury emitted from cremation. AEA Technology for DEFRA/WEG/SE, UK.

[126] Santarsiero A. et al. (2006) Mercury emission from crematoria. Ann. Ist. Super Sanità 42, 369-373

[127] Myers (2015) Quantifying mercury emissions resulting from the cremation of dental amalgam in Minnesota presented to Minnesota Pollution Control Agency (contract). Cited in Piagno & Afshari (2020)

[128] United Nations Environment Programme (2017). Toolkit for identification and quantification of mercury releases: reference report and guideline for inventory level 2 version 1.4

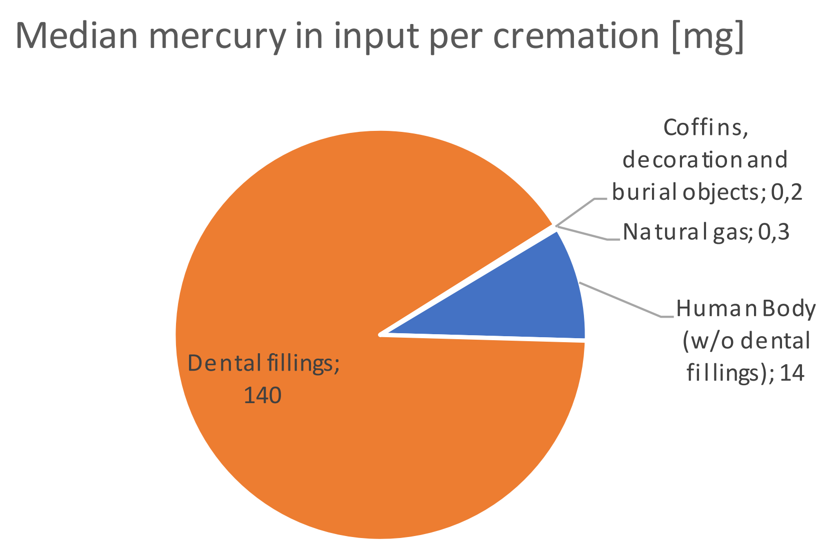
[129] EEA (2023) Air pollutant emission inventory guidebook. NFR: 5.C.1.b.v Cremation. Based on emission factors from 1992 (WebFIRE).

Country	Mercury content (medium) [mg]	Year of publication (data source may be older)
Canada/ British Colombia	1200	2020[130]
Germany	80-200 (individuals up to 7000)	2021[131]
USA	1000 (0.0022 lbs)	2023[132]

* This is an emission factor, not the actual mercury content per body

It is apparent that the contribution of mercury from dental amalgam dominates the total mercury content of the human body and all input of the cremator. Even if the low average mercury data from Germany are taken as an orientation, dental amalgam contributes at least 90% to the total mercury inventory (Figure 6-1:). Higher average mercury contents push this percentage to 99% and more.

Figure 6-1: Contribution of different sources to the overall mercury input per deceased (data for Germany, Ohle et al.[115])



A specific challenge for mercury abatement in crematoria is the wide range of the possible mercury input per cremation. While corpses with no amalgam fillings may have an almost negligible mercury content of around 10 mg, others may produce a spike of mercury input of several 1000 mg (Figure 6-2).

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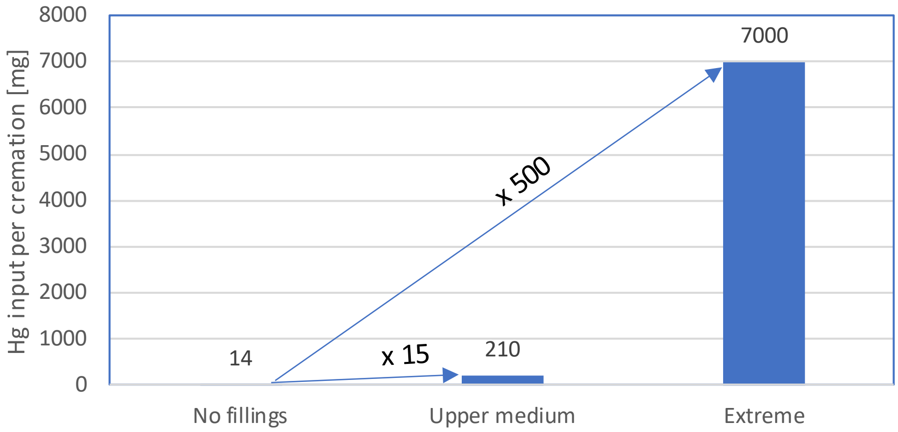
[130] Piagno & Afshari (2020) Mercury from crematoriums: human health risk assessment and estimate of total emissions in British Columbia. Canadian J. Publ. Health 111, p. 1011–1019

[131] Ohle et al. (2021)

[132] US EPA (2023) 2020 National Emissions Inventory Technical Support Document: Miscellaneous NonIndustrial NEC: Cremation – Human and Animal. https://www.epa.gov/system/files/documents/2023-04/NEI2020_TSD_Section29_Cremation.pdf

Figure 6-2 Minimum and maximum mercury input per cremation [mg]



6.1.1.1. Current and future trends in mercury content of human bodies

The mean number of fillings and mean total content of mercury per body is a product of dental health, the proportion of amalgam used at the time of filling therapy and the time interval between filling and death. Increasing dental health throughout Europe, the declining use of amalgam as a filling material (and ban due to come into force from 1 January 2025 according to Regulation 2017/852), and the limited lifespan of amalgam fillings mean that the total amount of mercury in living people in Europe is decreasing. However, this is not necessarily the case for the age cohorts that will die in the near future. The higher use of amalgam fillings in the past, combined with their often long life, will result in a continuing input of mercury into crematoria. Precise time series on the average presence of amalgam in the mouths of the deceased are not available. However, a significant decrease in the average amalgam content per body is to be expected, at least in the medium term. On the other hand, the increasing proportion of cremations in all types of burials across Europe may outweigh this effect.

A model was developed in the impact assessment for the revision of Regulation 2017/852[133] that predicts mercury inputs to crematoria up to the year 2030. It also describes the likely impact of the ban on dental amalgam on mercury emissions from crematoria.

[133] Logika (2023), Revision of Regulation (EU) 2017/852

6.2. Behaviour of mercury during combustion and flue gas treatment

6.2.1.1. Mercury chemistry at ambient and elevated temperatures

Elemental mercury is a noble metal with low tendency to undergo chemical reactions at ambient temperatures. The same applies to dental amalgam, which is a solid alloy of elemental mercury with silver and other metals. Strong oxidants, complexing agents and or high temperatures are necessary to transform elemental mercury into oxidized species such as Hg(I) or Hg(II)/Hg^{2+}. In crematoria, chemical reactions start once mercury is released from dental amalgam into the gas phase.

6.2.1.2. Primary speciation of mercury

Upon heating, mercury from dental amalgam is evaporated as elemental mercury. At typical temperatures maintained in the primary combustion chamber (min. e.g. 650°C, see Chapter 2.2.2) and the secondary combustion chamber (min. mostly 800-850°C) mercury is completely volatized. This process takes place within the first 10-30 minutes of the cremation and produces a sharp peak of mercury concentration in the raw flue gas[134]. No remains may be found in the ash[115]. The primary speciation of mercury in the raw flue gas is Hg(0). Continuous mercury measurements revealed that most of the mercury is released into the flue gas within minutes, producing concentration peaks of $Hg^{(0)}$ of several 1000 µg/Nm^3 when the cephalic part of the corpse (skull) is burned. However, smaller amounts of oxidized mercury (Hg^{2+}) may also be found. If no amalgam is present, mercury released from body tissues mainly appears as Hg^{2+} [116].

[134] Takaoka M. et al. (2021) Mercury removal from the flue gases of crematoria via pre-injection of lime and activated carbon into a fabric filter. Process Safety Environ. Protect. 148, 323-332

6.2.1.3. Reaction of mercury in the gas phase

The behaviour of mercury species in the gas phase of a combustion process is well known from investigations in coal combustion[135] [136] [137]. The result of this research is often transferred to cremation as some main principles are similar (carbon containing source, high combustion temperature, presence of reactants, cooling of flue gas, emission control techniques)[115].

At the initial high temperatures in the primary as well the secondary combustion chamber (> 800-850 °C), mercury remains in the elemental state. The further chemical fate of mercury depends on several factors including:

- Temperature of the flue gas and the cooling rate
- Presence of other elements and compounds that may interact with elemental and oxidized mercury (including chlorine and sulphur species)
- Dust concentration
- Completeness of combustion (soot content of the flue gas)
- Type of flue gas treatment devices used

As the flue gas cools below 600 °C, elemental mercury can be converted to oxidised forms via homogeneous gas reactions or via heterogeneous reactions on flue gas particles. Potential reaction partners are halogens (Cl, Br), acid gases (HCl, NOx) and oxygen (O_2). The reactions are kinetically controlled and strongly depend on the concentration of reactive radicals such as Cl·, O· and less so on the presence of compounds such as Cl_2 and HCl.

An important oxidation reaction is the interaction of Hg(0) with Cl radical to HgCl and further with Cl_2 to $HgCl_2$.

$Hg^{(0)} + Cl\cdot \rightarrow HgCl$

$HgCl + Cl_2 \rightarrow HgCl_2 + Cl\cdot$

This is a chain reaction as it continuously produces chlorine radicals for further reactions.

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[135] Galbreath K. C. and Zygarlicke C. L. (2000) Mercury transformations in coal combustion flue gas. Fuel. Proc. Techn. 65-66, 289-310 https://doi.org/10.1016/S0378-3820(99)00102-2

[136] Zhang L. et al. (2015) Mercury transformation and speciation in flue gases from anthropogenic emission sources: a critical review. Atmos. Chem. Phys. Discuss. 15, 32889–32929 https://doi.org/10.5194/acp-16-2417-2016

[137] Zhao S. et al. (2019) A review on mercury in coal combustion process: Content and occurrence forms in coal, transformation, sampling methods, emission and control technologies. Progr. Energy Combust. Sci. 73, 26-64. https://doi.org/10.1016/j.pecs.2019.02.001

6.2.1.4. Effect of NOx, SO_2 and H_2O

Nitrogen oxide, NO, may directly react with elemental mercury or enhance its oxidation by producing reactive oxygen radicals though the following reaction

$NO + O_2 \rightarrow NO_2 + O\cdot$

However, of higher relevance is the inhibiting effect of NO and SO_2 on the mercury/ chlorine reaction: NO as well as SO_2 may react with chlorine or chlorine radicals to NOCl and SO_2Cl_2 (and further with water to NO_2/SO_3 and HCl), thus reducing the number of reactive chlorine species and slowing down the oxidation of mercury.

6.2.1.5. Effect of O_2

The reaction of oxygen with mercury to HgO is slow and does not play a relevant role. HgO may nevertheless form through reactions such as

$HgCl_2$ -+ $H_2O \rightarrow HgO + 2\ HCl$

The compound is thermodynamically instable at temperatures above 320°C and it dissociates to elemental mercury and oxygen:

$2HgO \rightarrow 2Hg^{(0)} + O_2$

6.2.1.6. Heterogeneous reactions on the surface of dust particles

Another important feature are heterogeneous reactions on the surface of dust particles. Dust from combustion consists of inorganic minerals (e.g. Fe_2O_3) as well as traces of partially oxidized organic compounds and carbon. On the surface of dust particles reactions may take place between elemental mercury and with previously sorbed or chemically bound chlorine, for example (simplified):

$Fe_2O_3 + HCl \rightarrow Fe_2O_3\text{-}Cl + H\cdot$

$Fe_2O_3\text{-}Cl + Hg^{(0)} \rightarrow Fe_2O_3\text{-}HgCl$

$Fe_2O_3\text{-}HgCl + HCl \rightarrow Fe_2O_3 + HgCl_2 + H\cdot$

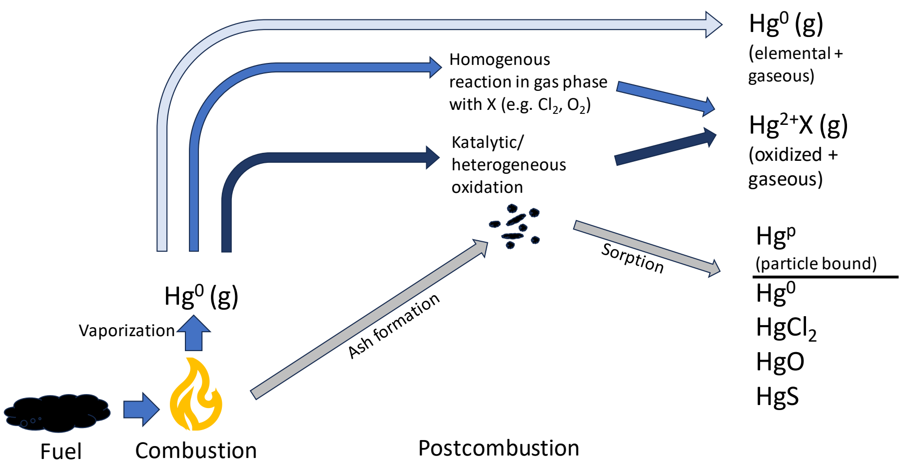
Consequently, a higher dust concentration in the raw gas improves the conversion of elemental mercury to oxidised species and overall is beneficial in removing mercury from the gas phase.

Carbon particles (soot) in the dust will also adsorb elemental mercury (see also section below). The worse and uncomplete the combustion the higher the soot concentration and the better elemental mercury is bound on particles.

As a result of chemical process in the gas phase, mercury may occur as gaseous compounds (Hg^{ox}), sorbed on particular matter (Hg^{p}) or may still be present in gaseous elemental form ($Hg^{(0)}$) (Figure 6-3).

Measurements in the raw flue gas of nine crematoria in Germany showed that mercury predominantly occurred in oxidized form (in 7 of 9 raw gas measurements and in all clean gas measurements after treatment)[138]. In another study, elemental mercury dominated in cases of a very high total mercury content in the flue gas[115]. From Japan, on the other hand a higher percentage of elemental mercury was reported[116]. The maximum (peak) total mercury concentration in the raw gas depends on the mercury input, the flue gas flow rate, and the duration of mercury evaporation. It may extend from values below 10 to above 14000 µg/m^3 [131,139]. The measurement of peak mercury levels is often complicated by the limited measuring range of the monitoring.

Figure 6-3: Mercury transformation processes in coal combustion (modified after Galbreath & Zygarlicke [135])



6.2.1.7. Sorption on activated carbon and catalytic filtration

In many crematoria, activated carbon mixed with lime (calcium carbonate/ calcium hydroxide) is injected into the gas stream or contained in a fixed bed in order to capture dioxines/furanes, hydrocarbons, mercury, sulfur dioxide as well as other heavy metals (See more detailed descriptions of abatement techniques in Section 5). Activated carbon acts as sorbent for mercury. The amount of

[138] Schetter G. and Bittig, M. (2020) Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen. UBA-Texte 26/2020.

[139] Umweltrelevanz und Stand der Technik bei Einäscherungsanlagen (Environmental impact and BAT of cremation facilities).Umweltbundesamt (Ed.), Texte 26, Dessau-Roßlau, 2020 https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-02-03_texte_26-2020_einaescherungsanlagen.pdf

elemental mercury that can be sorbed is limited by the accessible active inner and outer surface of the active carbon particles. Smaller particles have a higher specific sorption capacity and in addition, the path length of mercury diffusing into to the pores of the particles is shorter. The sorption capacity decreases with increasing temperature because mercury has a considerable vapor pressure at raw gas temperatures even as low as 100–150 °C.

More effective is the sorption of mercury if activated carbon is impregnated with sulfuric acid, iodine or bromine. Some self-impregnation is achieved with sulphur oxide in the flue gas. This increases the sorption of mercury as it may oxidise elemental mercury to solid mercury sulphate, iodide, or bromide[115].

In some facilities catalytical filters are employed to oxidize organic pollutants. The filter consists of a membrane to remove the dust, and a catalytically active needle felt. If these catalysts also support the oxidation of mercury is not clear. Particle-bound mercury can be removed but gaseous mercury passes the filter.

6.2.1.8. Retention of particle bound mercury and mercury speciation in clean flue gas

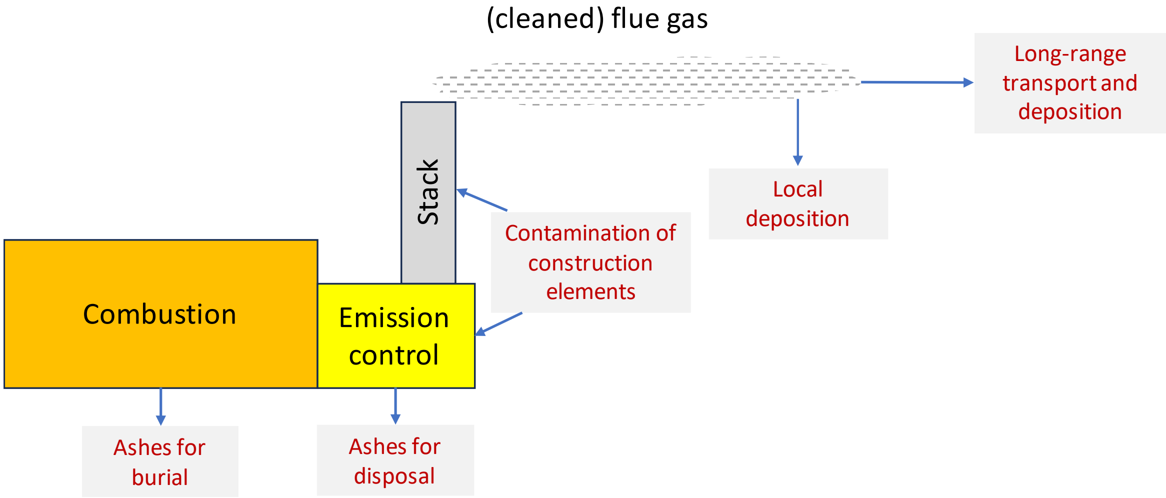
Particle-bound mercury can be separated via cyclones and dust filters. After dust filters, particle-bound mercury has a low share of the total mercury emission because oxidised and elemental mercury dominate. Almost all mercury in clean flue gas consists of oxidized species (> 90 %). Elemental mercury will dominate if no specific mercury retaining technique is employed or if the activated carbon filter is overloaded due to a mercury concentration pike and/or a long use.

6.3. Fate of mobilized mercury

6.3.1.1. Potential pathways of mercury inside a crematorium

Mercury mobilized from the cremated corpse may follow several pathways and end up in different waste types or environmental compartments (Figure 6-4).

Figure 6-4: Potential destinations of mercury released inside a crematorium



The primary waste form of cremation is the ash (intended for burial) as well as metallic/ceramic parts of the corpse and the coffin. The ash contains no or only low levels of mercury (< 1 ppm [115] [140]) which is expected given the high temperature the ash is exposed to.

Higher levels of mercury will be found in the dust, activated carbon and lime collected in the filters and possibly cyclones in the flue gas treatment system. Mercury concentrations of 120 to 530 mg were reported per kg filter dust[115]., depending on the completeness of the combustion and the related concentration of organic particles (soot).

Little information is available on the mercury contamination of construction materials[117]. In cases where the flue gas temperature allows the condensation of elemental mercury or mercury compounds from the flue gas, porous construction materials such as concrete or mortar may absorb mercury. Adsorption of mercury on corroded steel was also reported.[141]

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[140] Thomassen T., cited in Reindl J. (2015) Summary of References on Mercury Emissions from Crematoria. https://no2crematory.wordpress.com/mercury/

[141] Paton, L.; Crafts, P.; Clases, D.; Lindsay, T.; Zimmer, A.; Siboni H.; Gonzalez de Vega, R.; Feldmann, J.: The impact of corrosion on the adsorption of gaseous Hg^0 onto the surface of

Findings of slightly increased mercury levels in the hair of crematorium workers show that the presence of mercury in the cremation process may lead to an occupational exposure of employees[142]. The pathway is not clear, however and the results of the study were questioned[143].

6.3.1.2. Fate of mercury released from crematoria

Investigations of mercury concentrations in soil showed significantly elevated mercury levels around crematoria in the UK and New Zealand. These levels could also be correlated with the number of cremations at the sites checked[144,145]. A later study confirmed elevated concentrations in the direct proximity (< 100 m) of crematoria stacks but assessed that they were still in the range of background levels[146]. Short-term as well as long mercury concentrations in air around crematoria are considered to be far below reference concentrations[115,147].

Mercury released from the stack will be highly dispersed. Once emitted into the atmosphere, the three mercury forms elemental mercury (Hg^0), particulate mercury (Hg(p)), and oxidised gaseous mercury (Hg^{2+}) behave differently and influence the transport, deposition and eventual effects of mercury on ecosystems and human health.

6.3.1.3. Atmospheric transport and transformation

Elemental mercury is the most stable form in the atmosphere, where it can remain for months to over a year, allowing it to be transported globally[148]. It is relatively

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steels: Implications for decommissioning in the oil and gas industry. Journal of Hazardous Materials, Vol. 458, 15.9.2023 https://doi.org/10.1016/j.jhazmat.2023.131975

142 Maloney S. R. et al. (1998) Mercury in the hair of crematoria workers. Lancet 352 (9140), 1602 https://doi.org/10.1016/S0140-6736(05)61050-1

143 Nielsen J. B. & Grandjean P. (1999) Mercury in hair--but from where? Lancet 353 (9151), 502 https://doi.org/10.1016/S0140-6736(05)75179-5

144 Maloney S. R. (1998) Mercury emissions from crematoria. Master Thesis. – University of Northampton https://pure.northampton.ac.uk/en/studentTheses/mercury-emissions-from-crematoria-2

145 Nieschmidt A. K. & Kim, N. D. (1997) Effects of mercury release from amalgam dental restorations during cremation on soil mercury levels of three New Zealand crematoria. Bull. Env. Contamin. Toxikol. 58, 744-751. https://pubmed.ncbi.nlm.nih.gov/9115137/

146 Wood M. D. et al. (2008) Assessment of the mercury concentrations in soil and vegetation, including crops, around crematoria to determine the impact of mercury emissions on food safety. University of Liverpool's Institute.

147 Piagno H. & Afshari R. (2020) Mercury from crematoriums: human health risk assessment and estimate of total emissions in British Columbia. Can. J. Publ. Health 111. 1011-1019. https://doi.org/10.17269/s41997-020-00327-0

148 Pirrone N. & Mason R. (2009) Mercury fate and transport in the global atmosphere. Springer, Dordrecht.

inert but can be converted into oxidized gaseous mercury through interactions with atmospheric compounds such as ozone, halogens and hydroxyl radicals.

Oxidised mercury is much more water soluble than elemental mercury, making it easier to be removed from the atmosphere by precipitation (wet deposition) or by attachment to particles (dry deposition). This form has a shorter atmospheric lifetime (days to weeks) and is more likely to be deposited locally or regionally.

Particulate bound mercury can be deposited closer to the source but can also be transported over moderate distances depending on the size and type of particles.

6.3.1.4. Deposition and environmental impact

Mercury is mainly removed from the atmosphere by wet deposition/ precipitation, where it can reach water and soil. In aquatic systems it can be transformed by bacteria into methylmercury (MeHg), a highly toxic form that bioaccumulates in the food chain, particularly in fish. Mercury can also be deposited directly on surfaces (soil, plants) without precipitation, especially in its particulate or oxidised forms (dry deposition).

6.3.1.5. Global cycling

After deposition, mercury can be re-emitted into the atmosphere, particularly from soils and water bodies, making it part of a complex global cycle. Elemental mercury released by natural or anthropogenic processes, including incineration, also contributes to this cycle. Mercury from human activities can travel far from its original source, meaning that emissions from one region can affect ecosystems and populations on a global scale[149].

6.3.1.6. Health and environmental risks

Once mercury enters water bodies, it can convert into methylmercury, which is highly toxic and readily accumulates in fish, leading to significant human exposure, especially in communities reliant on seafood. Methylmercury exposure can damage the nervous system and is particularly harmful to developing foetuses as well as young children[150]

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[149] Selin N. E. et al. (2007) Chemical cycling and deposition of atmospheric mercury: Global constraints from observations. J. Geophy. Res. 112, D02308, 14 pp. https://doi.org/10.5194/acp-16-10735-2016

[150] Sheehan M. C. et al. (2014) Global methylmercury exposure from seafood consumption and risk of developmental neurotoxicity: a systematic review. Bull. World Health Organ. 92, 254-269F

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