Truth and Clarity on Mercury Regulation in UV Curing

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1. Abstract

The Minamata Convention on Mercury is an international treaty approved by 128 signatory nations on 9 October 2013. The treaty entered into force 16 August 2017 and was fully ratified in 2021. While its ultimate goal is clear - eliminate all global anthropogenic mercury use, implementation is not. This is because exemptions are allowed in the absence of viable mercury-free alternatives, and international treaties are entirely dependent on how ratifying parties institute and enforce compliant legislation within territorial boundaries. This paper summarizes 62 documents on global mercury use, legislation, handling, recycling, and disposal. It also addresses feasibility of light emitting diodes (LEDs) as an alternative to mercury vapor curing lamps. The intent is to clarify the regulatory landscape so that users of UV curing technology as well as industry suppliers can confidently plan for the future.

2. Executive Summary

There are no new restrictions in any country worldwide that specifically ban mercury UV curing lamps from production, use, export, import, or general shipment, and no new restrictions specifically addressing mercury vapor UV curing lamps are anticipated in the immediate term. Global regulatory policies driven by REACH, RoHS, TSCA/Lautenberg Act, and the Minamata Convention on Mercury as well as regulatory bodies such as the European Commission, the U.S. Environmental Protection Agency, and UN Environment are meant to reduce or eliminate anthropogenic mercury use. While complete mercury elimination is not possible today, restrictions and enforcement are expected to become stricter over time. The specifics of adopted policies, the means through which enforcement is pursued, and corresponding phaseout timelines, however, can sometimes be difficult to interpret and implement. As a result, legislation and policy crafted by REACH and RoHS in the EU, by the UK Parliament, and by the EPA in the U.S. along with legislation in other countries should be carefully and regularly reviewed with steps taken to best ensure compliance with local laws.

The policy that is most frequently referenced is the European Commission's RoHS 2 Directive. Even RoHS2, however, contains a scope carve-out that excludes large-scale stationary industrial tools (LSSITs) and large-scale fixed installations (LSFIs).[39] LSSITs are defined as *a large-scale assembly of machines, equipment, and/or components, functioning together for a specific application, permanently installed and de-installed by professionals at a given place, and used and maintained by professionals in an industrial manufacturing facility or research and development facility.*[39] LSFIs are defined as *a large-scale combination of several types of apparatus and, where applicable, other devices, which are assembled and installed by professionals, intended to be used permanently in a pre-defined and dedicated location, and de-installed by professionals*.[39]

For the UV curing industry, the scope carve-out has widely been interpreted to include printing presses, industrial curing chambers and tunnels, and converting lines among other industrial and commercial installations. As a result, the use of mercury UV curing systems in most production applications is generally understood to be exempt from RoHS restrictions indefinitely due to scope regardless of any specific ban on mercury UV curing lamps. Spare parts and upgrades to UV curing system installations made before any imposed ban are also allowed indefinitely. Furthermore, amendments to the Directive's Annex III have historically granted mercury UV curing lamps renewable five-year exemptions. The prior exemption adopted in 2016 was scheduled to expire in 2021 but was renewed through 2026 on 13 December 2021.[43]

Another policy making body that is frequently referenced is the Minamata Convention on Mercury. This is an international treaty that entered into force 16 August 2017, is ratified by 137 countries, and strives to eliminate all mercury from manufactured goods and processes. Over the coming decades, mercury regulatory policy will increasingly be driven by this treaty. Because implementation and enforcement of international treaties are executed at national levels, applicable legislation for each and every country potentially varies and is not always clear. While Minamata does not presently require a ban of mercury vapor UV curing lamps nor does it prevent their shipment internationally, it does require all Party nations to phase-out or take measures to reduce mercury when possible.[18]

Mercury (Hg) is a naturally occurring, highly reactive, dense element listed in the Periodic Table as a transition metal. It is classified as a neurotoxin since exposure can damage the brain and central nervous system and impair motor skills and sensory abilities. Humans are exposed to mercury through vapor inhalation, ingestion, injection, and dermal absorption. Toxicity levels vary significantly depending on the form of mercury, the dose, the rate of exposure, the age of the exposed person or fetus, and the route of exposure.[4,5,6] When mercury is naturally bound within the Earth, permanently disposed, or properly secured in products or storage containers above ground, it is generally safe from causing harm to humans and the environment. It becomes potentially dangerous, however, when released from its confines and dispersed within the global ecosystem. The World Health Organization (WHO) attributes the three dominant sources of mercury exposure to humans as outgassing of dental amalgam, ingestion of methylmercury contaminated fish, and occupational exposure.[7]

A discrete amount of elemental mercury contained inside mercury vapor lamps is necessary for UV lamps to function. The physics of elemental mercury result in emissions of ultraviolet, visible, and infrared electromagnetic wavelengths when mercury is vaporized into a high-temperature plasma within a sealed, inert gas-filled quartz tube under medium pressure. The amount of elemental mercury utilized within UV curing lamps varies across designs and lamp lengths; however, it is typically between 10 and 100 mg per lamp. UN Environment references an average of 25 mg per lamp for global inventory estimates. No other gas discharge material produces the same spectral output as mercury. Since the 1940s, UV curable chemistry has been intentionally formulated to react to the broad-spectrum output generated only by vaporized elemental mercury. Commercially available UV LED curing systems do not have the same spectral output and are, therefore, not a direct replacement.

Reputable UV curing lamp manufacturers source elemental mercury from non-mining sources such as exiting reserves and byproducts of other processes such as oil and gas refining. As a result, the production of UV curing lamps does not generally contribute to increases in global mercury inventories. Lamp manufacturers in regulated economies implement safety and quality protocols that protect employees during manufacturing processes and ensure all mercury is safely and securely contained within each lamp prior to shipment, during transit, and for the lamp's intended conditions of use and operational life.

When purchasing from qualified lamp suppliers, users should always receive sealed and tested mercury vapor lamps in proper packaging. Lamps not sourced from reputable suppliers, properly packaged, and clearly marked by the manufacturer should not be used. In many cases, aftermarket lamps void UV curing system warranties, compromise the integrity of the system, and negatively affect curing performance and lamp life. At the location of intended use, lamps are safely and securely installed within lamphead assemblies which are then installed in larger manufacturing systems. On the rare occasion that a mercury vapor lamp breaks, clean-up procedures established for any type of mercury-added gas discharge lamp should be followed. Procedures written for fluorescent lamps are generally applicable to UV curing lamps.

Since emissions to air and releases to water from mercury-added products primarily occur during waste disposal,[3] mercury vapor lamps should never be discarded with bulk trash collection. When discarded with general trash, mercury inside lamps can be exposed to the biosphere when lamps are crushed and either incinerated or buried. Fortunately, mercury pollution from UV curing lamps is avoidable by recycling lamps through facilities that ensure lamp components are separated and spent mercury is safely and securely captured. Reclaimed mercury goes into long-term secure storage, permanent disposal, or is processed through established and documented protocols that safely re-introduce elemental mercury into permissible manufacturing channels.

UV LEDs emit ultraviolet energy without the use of mercury and, therefore, represent the most promising mercury-free alternative to conventional UV curing systems. UV curing applications presently able to transition to UV LED are going through the conversion process now. This includes many but not all aspects of digital inkjet, screen, flexo, and offset printing; structural bonding adhesives; fiber optic primary coatings; and wood fillers. As confidence builds and technology and application feasibility improve, more users and markets will follow, which is ultimately the goal of Minamata. This will occur regardless of regulatory involvement since UV LED curing, with continued development, has the potential to be the preferred emitting source for all curing applications. In the meantime, users of UV curing are encouraged to educate themselves on the technology, actively engage in UV LED curing process development, and recycle all mercury vapor lamps at end of useful life.

In the unlikely scenario that regulators proceed with a global ban on mercury vapor lamps in the near future, it will not produce an immediate and complete shift to UV LED technology. It simply is not technically, economically, or practically possible due to the wide range of UV curing applications and processes across all industries that have not yet been suitably developed for LED and the large existing installation base that must be converted. An all-inclusive ban disproportionately favors economically advantaged countries at the expense of third world users. Furthermore, a ban on mercury vapor UV curing lamps will not make a significant impact in reducing global anthropogenic mercury use and environmental pollution due to the safe practices of the industry, the low level of mercury content within the lamps, the reclamation process available through recycling, and the rapidly growing demand and use of mercury by Artisanal Small-Scale Gold Mines (ASGMs) in Asia, Africa, and South America and vinyl chloride monomer (VCM) producers in China.

A premature total use ban on UV curing lamps will primarily serve to destroy the value of existing UV curing assets, inhibit production capabilities of manufacturers, and drive-up product prices when manufacturers have no other option than to embrace less desirable alternative technologies. This includes various curing and drying technologies that are less efficient, do not deliver comparable end use product performance requirements, consume higher levels of energy, result in inferior and/or more expensive end-use products, and lead to other negative consequences on the environment such as the emission of greenhouse gases and greater carbon footprints.

On the bright side, the global community should be highly encouraged by the potential of UV LED curing technology to facilitate the continued reduction and eventual elimination of mercury-added products. In fact, UV LED curing is well positioned to steadily capture a significant portion of UV curing applications over the next one to two decades. While innovation rarely happens overnight, the viability of UV LED technology continues to progress and, in due time, will be the primary driver in eliminating use of mercury vapor lamps in the UV industry. Concerted efforts to recycle spent lamps will also ensure that more mercury is permanently disposed and prevented from freely circulating within the biosphere.

3. Mercury and its Forms

Mercury is a naturally occurring, highly reactive, dense element classified in the Periodic Table as a transition metal. It is assigned European Community (EC) Number 231-106-7 and Chemical Abstracts Services (CAS) Registry Number 7439-97-6. Elemental mercury predominantly exists as inorganic liquid or vapor and freezes solid at temperatures below -38.72°C (-37.70°F). Pure mercury is not contaminated by other substances, cannot be chemically broken down, and is never destroyed.

Elemental mercury (Hg) bonds easily with chlorine (Cl), oxygen (O), sulfur (S), carbon (C), and various carbon containing materials to form numerous chemical and physical species classified as either inorganic or organic compounds. All inorganic salt compounds containing Hg (II) ions are referred to as mercuric. Less common inorganic salt compounds containing Hg (I) ions are described as mercurous. When elemental mercury dissolves into metals such as gold, silver, copper, zinc, and tin, stable alloys known as amalgams are formed. Amalgams are not chemical compounds and are better described as chemical mixtures. Refer to Figure 1.

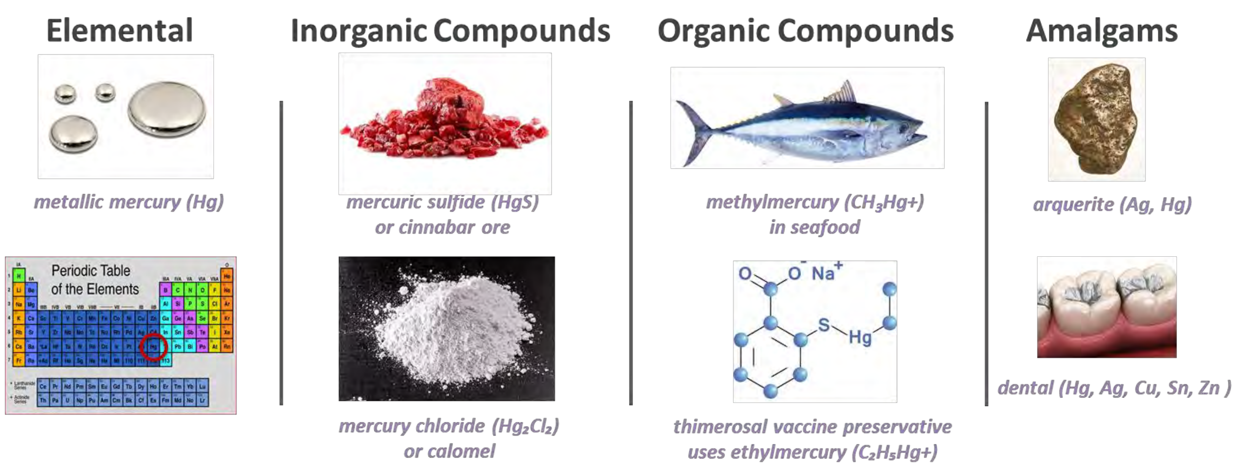

Figure 1: Mercury is highly reactive and forms numerous chemical and physical species classified as elemental, inorganic and organic compounds, and amalgams.

Elemental Mercury

Elemental mercury is synonymous with metallic mercury, liquid mercury, quicksilver, and hydrargyrum, which is the source of chemical symbol Hg. In pure form, mercury has the familiar consistency shown in Figure 2 and is scientifically denoted Hg(0) or Hg^0. Its chemical and physical properties are listed in Figure 2 and include being liquid at atmospheric pressure and temperature, conducting electricity, and emitting ultraviolet light when elevated to a plasma state within an inert gas environment. Each of these qualities make elemental mercury instrumental to the functionality of medium-pressure mercury vapor UV curing lamps as well as other gas discharge lighting technologies.

Except for vaporized mercury dispersed throughout Earth's atmosphere, pure elemental mercury is rarely isolated on its own in nature. This is due to the ease with which mercury bonds to other elements, its ability to quickly dissolve within various substances including metals, and the fact that mercury vaporizes into the atmosphere gradually at room temperature and more rapidly when heated.

Consequently, mercury tends to exist at the surface and beneath the surface of the Earth as more stable inorganic and organic compounds and mixtures.

Properties of Elemental Mercury

- highly reactive
- dense transition metal
- liquid at room pressure and temperature
- freezes below -38.72°C
- cannot be chemically broken down
- cannot be destroyed
- conducts electricity
- emits UV when elevated to a plasma state

Figure 2: Elemental Mercury (Hg^0).

Inorganic Mercury Compounds

Inorganic mercury compounds form when mercury reacts with elements other than carbon. According to mindat.org, 88 different inorganic mineral species contain essential mercury, the most notable being mercury sulfide (HgS) ores.[1] Both mercuric sulfide and mercury (II) sulfide are equivalent scientific descriptors of mercury sulfide ores with common names being cinnabar, hypercinnabar, and metacinnabar. Cinnabar ore is the historical source of vermillion pigment and is noted by the distinctive red color visible in Figure 3.

Figure 3: Mercuric Sulfide (HgS) or Cinnabar Ore.

Evidence of mercury's many physical forms is illustrated by comparing elemental mercury (Hg^0) in Figure 2, cinnabar ore (HgS) in Figure 3, and inorganic mercury chloride or calomel (Hg_2Cl_2) in Figure 4. In stark contrast to the liquid and vapor forms of elemental mercury and the rock-like consistency of cinnabar, calomel exists as crystalline granules.

Figure 4: Mercury Chloride or Calomel (Hg_2Cl_2).

Of all the forms of mercury, cinnabar is the most accessible, naturally forming variation in the Earth and is the primary source of mined elemental mercury. Once extracted, cinnabar rocks are crushed into a fine powder and heated in a furnace to break the bonds between mercury and sulfur. Elemental mercury contained in the ore is then separated using a distillation process that first vaporizes and then condenses mercury into a form that is up to 99.9% pure Hg^0.

Organic Mercury Compounds

When mercury interacts with carbon, organic mercury compounds form. Two common examples are methylmercury (CH_3Hg+) and ethylmercury (C_2H_5Hg+). Methylmercury is present in all living organisms as it is easily absorbed by the skin and gastrointestinal tracts of humans, animals, and aquatic life. Methylmercury is produced biologically when microbes in aquatic water and soil metabolically convert inorganic mercury into methylmercury. Methylmercury produced by single cell organisms ultimately works its way up the food chain as larger species feed on contaminated smaller species. This is referred to as biomagnification. By contrast, ethylmercury is synthesized in production and lab environments and most often exists as a component of other compounds. For example, thiomersal/thimerosal ($C_9H_9HgNaO_2S$) is an ethylmercury containing compound that is often used as a preservative in medical products including some vaccines. When methylmercury and/or ethylmercury are absorbed by living creatures, the toxic compounds deposit within tissue and remain in the body unless biological processes cycle them away.

4. Mercury-Added Products

When mercury in any form is intentionally added to a product during manufacturing and remains part of the final product for the sole purpose of performing a necessary function, the product is classified as a mercury-added product. In others, mercury is part of chemical manufacturing processes that often leave trace amounts of residual mercury in the final product. Examples include button-cell batteries used in small electronic devices; lamps used in general lighting, disinfection, sterilization, tanning, and UV curing; measuring devices; dental amalgams; and formulated chemicals such as cleaning products, cosmetics, pharmaceuticals, laboratory ingredients, and coating materials. Examples are shown in Figure 5.

Figure 5: Examples of Mercury-Added Products.

Many types of gas discharge lamps are classified as mercury-added products. This is because a discrete amount of mercury is placed inside various lamp assemblies for the purpose of emitting light when vaporized. Without mercury, gas discharge lamps simply do not function. It should be noted that the amount of elemental mercury used in all types of lighting technologies is relatively small compared to other current and previously discontinued mercury-added products. Lamps that contain mercury include fluorescent lamps, compact fluorescent lamps (CFLs), bug zappers, black lights, UVA tanning lamps, UVC germicidal lamps, high output (HO) fluorescent lamps, cold-cathode lamps, high intensity discharge (HID) lamps, metal halide (MH) lamps, neon lights, and medium-pressure UV curing lamps including electrode arc and microwave types.

Global initiatives encourage the use of mercury alternatives whenever possible and often prohibit use of mercury in newly engineered items. As a result, general use of mercury in manufactured goods has decreased in recent decades and will continue to do so as economically and technologically viable alternatives are identified and adopted. Concerted efforts to move away from mercury have resulted in sales of mercury-added products in the United States decreasing more than 97% since 1980.[2] While a similar statistic could not be sourced for the European Union, the decrease in Europe is likely similar and possibly greater due to more stringent regulations being adopted earlier.

5. Means through which Mercury Enters the Biosphere

When mercury is naturally bound within the Earth, permanently disposed, or properly secured in sealed products and storage containers above ground, it is generally safe from direct human exposure and environmental harm. It becomes potentially dangerous, however, when released from its confines and dispersed within the global ecosystem or biosphere. Mercury, primarily in inorganic form, enters the biosphere via two pathways: gas and vapor emissions to air and direct and indirect releases to water. Once free, mercury migrates easily, readily changes form, and potentially exposes all organisms with which it makes contact. This *Mercury Cycle* is illustrated in Figure 6.

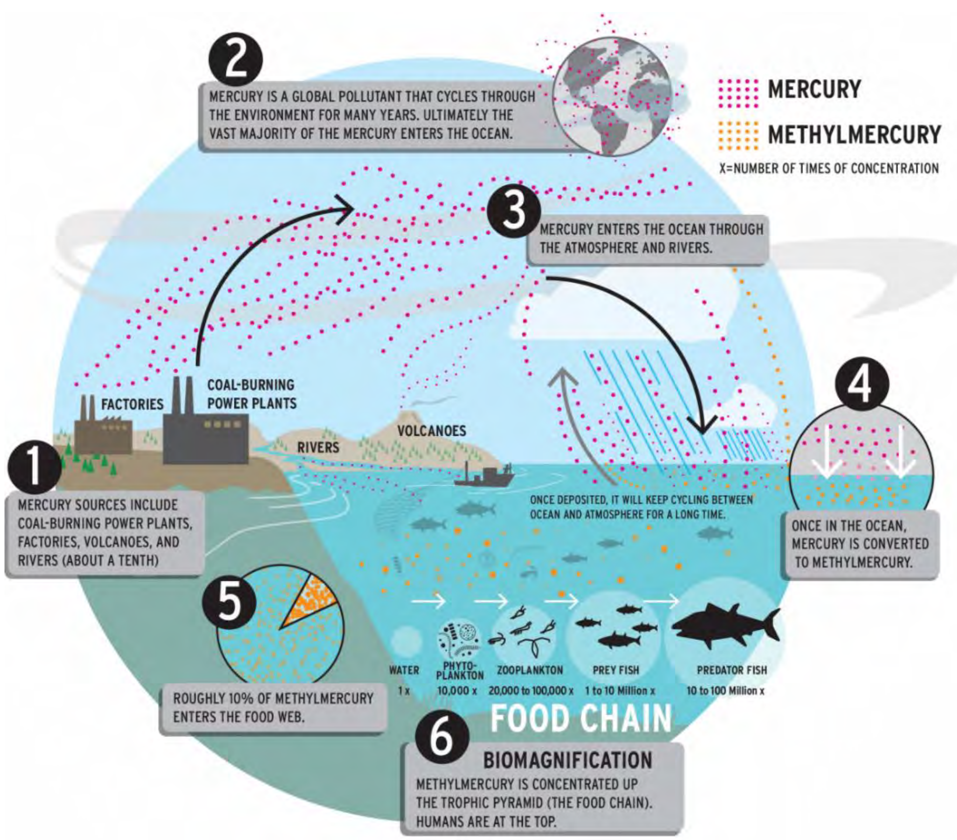

Figure 6: The Mercury Cycle. Graphic courtesy of Harvard Magazine. *The "Global Chemical Experiment", Elsie Sunderland maps invisible ocean pollutants. Author Courtney Humphries*. July – August 2018.

The United Nations Environment Programme (UN Environment) tabulates regional air emissions and water releases every five years (2010, 2015, 2020, etc.) with a detailed report published approximately three years later (2013, 2018, 2023, etc.). The most current UN global data on mercury emissions and releases was collected in 2015 and is summarized in its 2018 assessment. For the purposes of UN Environment reporting, mercury landfill waste disposal and soil contamination resulting in ground water runoff is captured within water release data.

The 2015 UN Environment data estimates annual mercury emissions to the atmosphere as stemming from natural environmental occurrences (10%), anthropogenic activity (30%), and legacy re-emissions due to prior anthropogenic activity (60%).[3] Natural mercury pollution occurs when volcanic eruptions blast large amounts of mercury stored within the Earth directly into the environment; when forest fires release mercury from soil and vegetation; and when mercury outgasses from rocks, soil, and oceans. When mercury is directly or indirectly emitted to air or released to water by human activity, it is referred to as anthropogenic. 60% of all global anthropogenic mercury emissions are currently from coal combustion and artisanal small-scale gold mining (ASGM).[3] ASGMs are also responsible for 38% of all global anthropogenic mercury releases to water.[3]

Humans introduce mercury into the biosphere by mining and distilling cinnabar, vaporizing elemental mercury during the mining of precious metals, and through the burning of fossil fuels, particularly coal. Whenever fossil fuels such as natural gas, oil, and coal are extracted, refined, processed, and burned, trace amounts of mercury trapped within the fuel are released into the environment in varying quantities that largely depend on the material composition of the fuel, processing steps utilized, and implemented retention safeguards. Other leading anthropogenic sources of mercury include metal and cement production, waste and waste treatment, and ore mining and processing.

According to UN Environment, anthropogenic mercury emissions to air totaled 2200 tonnes in 2015 with most occurring in Asia (49%), South America (18%), and Sub-Saharan Africa (16%).[3] This followed a similar global distribution to 2010 but was 20% greater in magnitude.[3] Stationary combustion of fossil fuels and biomass is responsible for about 24% of these emissions with coal burning contributing the largest portion at 21%.[3] Other contributors included emissions from metal (15%) production, cement (11%) production, and waste streams stemming from discarded mercury-added products as well as manufacturing processes (7%).[3] While successful efforts to curtail mercury emissions in the European Union and North America have resulted in modest decreases, they have been offset by increases in emissions elsewhere.[3]

With respect to mercury releases to water, artisanal and small-scale gold mines (ASGMs) were responsible for nearly 1220 tonnes of mercury introduced to terrestrial and freshwater environments in 2015.[3] This was the result of discharges to soil and direct releases to water.[3] All other water pollution sources combined contributed a total of 580 tonnes and primarily stemmed from waste treatment (43%), ore mining and processing (40%), and energy (17%).[3]

Once mercury enters the biosphere, it easily cycles back and forth in various forms throughout the atmosphere, bodies of water, sediment, plants, and animals with some mercury eventually working its way far below the ocean floor or depositing in other hard to access parts of the Earth. While these resting places may serve to further restrict migration and human access, the natural trapping of mercury within the Earth can take decades if not centuries to occur.

6. History of Anthropogenic Mercury Use

According to numerous historical references, the existence of elemental mercury as a unique substance has likely been known for more than 3.5 millennia; however, modern mining and industrial manufacturing have driven the most significant increase in human use. UN Environment has generally referenced 1850 as the baseline year of global mercury increases due to anthropogenic activities. New studies, however, seem to indicate that precious metals mining may have played a greater role as early as the 16th century.[3] While this perspective on the significance of earlier mining pollution is new, it suggests that all mining activities prior to 1920 may account for two-thirds of legacy anthropogenic mercury currently circulating in the world's oceans.[3] Since 1920, coal combustion and other industrial activities likely contributed the other third.[3]

Manmade products, processes, and applications that relied on mercury in all its various forms include but are not limited to cosmetics, jewelry, pharmaceuticals, fertilizers, pesticides, felt production, scientific and personal instrumentation and devices, batteries, medical and dental procedures including dental amalgam fillings, lighting technology, disinfectants and antiseptics, mining of precious metals, electrical components such as relays and switches, the production of vinyl chloride monomer (VCM) used in the manufacture of poly vinyl chloride (PVC) products, and chlor-alkali production processes that generate sodium hydroxide (NaOH) also known as caustic soda, potassium hydroxide (KOH) also known as caustic potash, and chlorine. Despite mercury's ability to make numerous products and processes viable, its substantial use over the last 500 years has come at a cost as improper handling and disposal, overexposure, and accidents have resulted in toxic environmental contamination, poisoning, and loss of life.

7. Mercury Toxicity

The full extent of mercury's toxicity is a relatively recent unraveling. Curious individuals who personally witnessed mercury's negative effects on the human body conducted observational studies during the 1800s and 1900s. In the 1950s, a neurological disease was identified and later attributed to mercury exposure. It was named Minamata disease after the city in Japan where highly concentrated inorganic mercury pollution from industrial wastewater discharged into Minamata Bay where it was transformed by single cell organisms into organic methylmercury. The methylmercury poisoned the community's supply of fresh seafood and subsequently the local population that consumed it. This is illustrated in *The Mercury Cycle* graphic previously provided in Figure 6. It was not until the 1960s and 1970s, however, that mercury's link to severe neurological issues, gastrointestinal distress, and organ damage was established and began to be acknowledged by the international community.

The medical and scientific communities now understand that exposure to mercury can lead to complications in both fetal and childhood development, damage to the brain and central nervous system, kidney failure, and even loss of life. Mercury is a neurotoxin that affects motor skills and sensory abilities. It can cause tremors, inability to walk, and convulsions. Exposure occurs through vapor inhalation, ingestion, injection, and dermal absorption. Human toxicity levels, however, vary with the form of mercury, the dose, the rate of exposure, the age or development stage of the exposed person or fetus, and the route of exposure.[4,5,6] Refer to Figure 7 for a summary. The World Health Organization (WHO) attributes the three dominant sources of mercury exposure to humans as outgassing of dental amalgam, ingestion of methylmercury contaminated fish, and occupational exposure.[7]

Overexposure Can	Factors Affecting Toxicity	Methods of Exposure
affect motor skills and sensory abilities	form of mercury	vapor inhalation
cause tremors, inability to walk, convulsions	dose	ingestion
cause damage to brain and nervous system	rate of exposure	injection
lead to kidney failure	method of exposure	dermal absorption
lead to complications in fetal and childhood development	age or development stage of person/fetus	
result in loss of life		

Figure 7: Mercury is classified as a neurotoxin with varying degree of toxicity and several methods of exposure.

8. Dental Amalgam Fillings

Historical records reference the use of amalgam dental fillings made of unspecified materials by the Chinese in 659 and Johannes Stockerus, a German physician, in 1528.[8,9] The first detailed ingredients list and mixing instructions were documented in 1578 and specified a mixture of 100 parts mercury with 45 parts silver and 900 parts tin.[7] The process and mixture were further developed in England and France in the 1820s. Despite noticeable side effects reported in some people receiving dental fillings as early as the 1830s, mercury amalgam remains the most widely used material for filling teeth.[10] A rendering of mercury amalgam dental fillings is shown in Figure 8.

Figure 8: Mercury Amalgam Dental Fillings.

The dental industry has significantly improved the mercury amalgam filling process over the last 150 years. When properly administered, mercury amalgams, frequently referred to as silver fillings, are considered safe by numerous governmental agencies, regulating bodies, and professional organizations affiliated with the dental industry who regard the risk of mercury exposure to humans as minimal. This includes the American Dental Association (ADA), the Canadian Dental Association (CDA), the U.S. Center for Disease Control (CDC), and the U.S. Food and Drug Administration (FDA). It is vitally important, however, that all discarded dental amalgam be retained and properly disposed through mercury collection and recycling centers to avoid anthropogenic releases to the environment.

Modern mercury amalgam fillings contain up to 50% mercury by weight with the remaining portions a mixture of silver, copper, tin, and zinc. While the amalgam size varies according to patient need, the amount of mercury used per filling is typically a gram or less.[11] UN Environment references an average value of 0.8 grams per filling in global inventory calculations.[12] While most of the prepared mercury amalgam mixture fills the tooth cavity and remains with the tooth, a small portion of the mixture is left unused. Any unused portion as well as fillings that are later removed are discarded as waste.

When amalgam is being set in a tooth or removed from a tooth, a small amount of mercury has the potential to outgas. The risk is that mercury gas or vapor is absorbed into the bloodstream and body tissue. Once a filling is set, some believe outgassing during the life of the filling and its effects on the human body are minimal. Others claim mercury is regularly released from amalgams due to chewing, brushing, and corrosion. While studies are inconclusive, even low doses of elemental mercury are potentially harmful.

While mercury-free composite resins are now widely available, preferred, and more cosmetically appealing, amalgam is considerably less expensive. For this reason, as well as its durability and ease of use, mercury amalgam fillings continue to be placed in over one billion teeth annually.[13] Unlike amalgam fillings, dental crowns do not contain mercury and are primarily made from stainless steel, gold alloys, ceramic, porcelain, and porcelain fused to metal.

In 2008, Denmark, Norway, and Sweden completely banned mercury amalgam dental fillings, and in 2018, the EU and the UK, in collaboration with the British Dental Association (BDA) and the Council of European Dentists (CED), prohibited all use in pregnant woman and children under the age of 15. In 2019, the EU and the UK eliminated bulk use and stipulated dental facilities be equipped with separation and retention equipment. While originally targeted for 2020, plans for the complete elimination of mercury fillings in the EU and the UK have since been extended to no later than 2030.[14] Finalization of the date is pending further research and greater understanding regarding the feasibility of phasing out use in the dental industry over the next decade.[14]

On 25 March 2022, during the fourth meeting of the Conference of the Parties (COP) for the Minamata Convention on Mercury, an amendment passed to end the use of mercury dental amalgam in deciduous teeth of children under the age of 15 and in pregnant and breastfeeding women. The amendment takes affect 25 December 2022.[15] Implementation and enforcement of the amendment now move to each of the 137 ratifying parties and the respective governmental agencies in those countries responsible for compliance. In Europe, this is the European Commission and member nations. In the U.S., this is the Food and Drug Administration (FDA).

9. Aquatic Life

Direct mercury discharge into water systems as well as indirect leaching into soil and runoff into bodies of water occurs through mining, energy production, industrial processes and accidents, irresponsible storage and waste disposal, improper use and handling, volcanic eruptions, and forest fires. As previously stated, artisanal and small-scale gold mines (ASGMs) are the single biggest anthropogenic source of mercury pollution and are responsible for 38% of all mercury releases to water worldwide.[3] Mercury also enters global water systems through wet and dry deposition of new and legacy mercury emissions circulating throughout the atmosphere.

Whenever inorganic mercury is present in aquatic environments, single cell organisms in sediment and water transform it into organic methylmercury (CH_3Hg^+). Methylmercury poisons aquatic life and the subsequent food chain through biomagnification as larger species feed on contaminated smaller species. Since seafood is the main source of protein for one billion people worldwide,[3] contaminated aquatic life has the potential to harm a large portion of the global population that consumes regular portions of seafood containing high levels of methylmercury. This includes seafood harvested and consumed near the source of mercury pollution, seafood harvested and consumed away from the original source of mercury pollution, and contaminated seafood harvested and commercially shipped to markets and restaurants around the world.

Global communities who significantly rely on contaminated seafood for daily survival are most at risk to methylmercury exposure. Elsewhere, consumer warnings have increasingly been issued against heavy consumption of seafood species known to have higher levels of methylmercury. This predominantly applies to larger and longer living types such as tilefish, swordfish, shark, and tuna, among others. As a precaution, pregnant women are strongly advised by medical doctors to avoid all seafood consumption to protect fetal and early childhood development. Easy to follow charts and carrying cards as shown in Figure 9 are regularly updated and published by various organizations around the world.

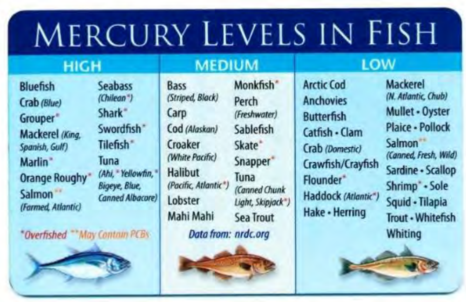

Figure 9: Mercury content guide for safe fish consumption as published by the Natural Resources Defense Council (NRDC).

10. Artisanal Small-Scale Gold Mines (ASGMs)

In recent decades, occupational exposure to mercury has been dramatically reduced in countries and industries that regulate, monitor, outlaw specific uses and practices, and require implementation of safeguards and retention equipment. A significant source of direct human occupational exposure, however, exists for individuals working in artisanal and small-scale gold mines (ASGMs). ASGMs are frequently non-licensed mines that use elemental mercury to extract gold from silt and dust.

Using an open bowl, miners in ASGMs add liquid mercury directly to crushed rock, silt, and dust containing small gold particles. The mercury quickly dissolves into the gold to form solid amalgams. This allows miners to easily separate loose material that is not part of the amalgam and does not contain much gold. A handheld blow torch or other high temperature heat source is then used to vaporize the mercury from the amalgam leaving gold and about 5% residual mercury in the pan.[17] Unfortunately, the vaporized mercury is released directly into the air surrounding the miners who subsequently inhale it as shown in the following photo.

Figure 10: Mercury is commonly and dangerously used by ASGM miners.

Collectively, artisanal small-scale gold mines furnish 20% of the entire global gold supply[16] and are the single largest source of mercury pollution in the world.[3] ASGMs are operated in more than 70 countries[17] where many mines are poorly regulated, embedded with corruption, and highly dependent on child labor. In 2018, it was estimated that approximately 15 million individuals work in the ASGMs of Africa, Asia, and South America and are exposed to dangerous levels of mercury on a regular basis.[2] This includes 4.5 million women and 1 million children.[16] In addition, 100 million more individuals reside in the vicinity of artisanal and small-scale gold mines and are subsequently exposed to mercury due to proximity.[3]

11. Global Initiatives Regulating Mercury Use

Local, national, and economic organization governing bodies as well as multi-nation and non-governmental organizations (NGOs) establish and routinely update policy stipulating that the most dangerous and most toxic materials must be substituted with suitable alternatives whenever they are identified. Harmful materials meant for replacement are generally referred to as substances of very high concern (SVHC). Mercury is an example of an SVHC. This designation drives legislation and policy that regulates how mercury is obtained, used, sold, transported, imported, exported, and disposed.

Due to the ease with which mercury migrates throughout nature; the efficiency with which it vaporizes and changes form; increased globalization of manufactured and internationally shipped goods; and the detrimental biological effects caused by mercury, local, national, and regional level policy efforts meant to curb use are insufficient on their own. As a result, growing desire to eliminate all industrial and consumer use of mercury is increasingly shifting to a coordinated global effort.

Policies created under this global effort are implemented at national levels as a combination of legally binding laws, ratified international treaties, enforceable regulations, suggested guidelines, and best practices. The overarching and collective goal is to limit global circulation and use of mercury. While the release and movement of both natural and legacy mercury by the Earth will continue indefinitely, regulatory policy is meant to reduce new emissions to air and new releases to water from anthropogenic activities. This includes phasing out mercury-added industrial and consumer goods and manufacturing processes that involve mercury *whenever viable alternatives are established*.

The following list details primary legislation on mercury as well as the regulatory bodies that create and drive mercury-related policy. This is not an exhaustive list as other legislation and environmental organizations around the world predate or exist in addition to those documented here. As a result, inception dates are provided solely for historical context and are not meant as a timeline of global efforts on mercury regulation. Links for each organization or legislation are included. The respective web sites should be reviewed for greater understanding beyond the brief summaries provided.

- European Commission: Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), 2007
  www.ec.europa.eu/environment/chemicals/reach/reach_en.htm

- European Commission: Restriction of Hazardous Substances (RoHS and RoHS 2), 2003 and 2011
  www.ec.europa.eu/environment/waste/rohs_eee/index_en.htm

- European Union (Withdrawal) Act 2018
  www.legislation.gov.uk/ukpga/2018/16/contents/enacted

- United States of America: Environmental Protection Agency (EPA), 1970
  www.epa.gov/mercury

- United States of America: Toxic Substances Control Act (TSCA), 1976
  www.epa.gov/laws-regulations/summary-toxic-substances-control-act

- United States of America: The Frank R. Lautenberg Chemical Safety for the 21st Century Act (Lautenberg Act), 2016
  www.epa.gov/assessing-and-managing-chemicals-under-tsca/frank-r-lautenberg-chemical-safety-21st-century-act

- United Nations Environment Programme (UN Environment), 1972
  www.unenvironment.org/explore-topics/chemicals-waste/what-we-do/mercury

- Minamata Convention on Mercury, 2013
  www.mercuryconvention.org

REACH and RoHS are bodies of legislation that have been adopted and approved by the European Commission and its 28 member nations. REACH focuses on the *registration, evaluation, authorisation and restriction of chemicals*. It requires manufacturers and importers that use chemical substances to collect information on the respective properties for the purposes of facilitating safe handling. This information is submitted and housed in a database in the European Chemicals Agency (ECHA) in Helsinki, Finland. Whereas REACH focuses on the broader use of chemicals, RoHS directs efforts on the use of hazardous substances in *electrical and electronic equipment* (EEE) as well as the subsequent *waste stream of electrical and electronic equipment* (WEEE).

The United Kingdom passed the European Union (Withdrawal) Act 2018. This Act wrote into UK law the treaties that were rendered null and void when the United Kingdom withdrew from the EU on 31 December 2020. REACH and RoHS 2 are part of this framework. As a result, the standards of REACH and RoHS 2 apply equally to the UK as they do to the EU. The primary difference is that the EU institutions referenced in the EU Directives have been replaced by UK institutions.

Similarly, in the United States of America, the EPA writes, implements, and enforces regulation that directly supports environmental and human health related law adopted by the U.S. Congress and approved by the U.S. President. The Toxic Substances Control Act (TSCA) is an Act of the U.S. Congress that specifically authorizes the EPA to require reporting, record-keeping, testing requirements, and restrictions relating to chemical substances and/or mixtures. TSCA was passed in 1976 and amended in 2016 with the Lautenberg Act. Excluded from TSCA are food, drugs, cosmetics, and pesticides among various other items which are the responsibility of other organizations within the federal government such as the Food and Drug Administration (FDA).

The United Nations Environment Programme (UN Environment) exists within the United Nations and is headquartered in Nairobi, Kenya. UN Environment drives initiatives related to climate change, disasters and conflicts, ecosystem management, environmental governance, chemicals and waste, resource efficiency, and environment under review. As previously noted, UN Environment estimates regional air emissions and water releases of mercury every five years (2010, 2015, 2020, etc.) with a detailed report published three years later (2013, 2018, 2023, etc.). Since the 1970s, UN Environment, previously referred to as UNEP, has been a major driving force in bringing global attention to the toxicity and environmental harm caused by mercury.

Working meetings held by UN Environment in 2007 and 2008 led to the decision in 2009 that an international treaty was necessary to make mercury policy legally binding and effective. From 2010 to 2013, an international negotiating committee drafted the working document for the Minamata Convention on Mercury. The treaty language was adopted in early 2013, and the Convention officially opened on 9 October 2013 with 128 signatory countries. The treaty entered into force 16 August 2017, and as of March 2022, the Minamata Convention on Mercury has been ratified by 137 nations. Unlike other organizations and initiatives which focus on numerous environmental issues and a broad range of hazardous substances, the Minamata Convention on Mercury is solely dedicated to protecting human health and the environment from the adverse effects of mercury.

Regulatory policy put forth by the EU, the UK, the U.S., the UN, and Minamata along with other countries and organizations that is legally implemented at national levels requires compliance by all companies manufacturing within and/or selling into the *applicable geographical area of legal sovereignty*. The EU requires member nations to incorporate EU Directives and amendments into national legislation within a three-year period and within shorter periods when specifically stated. The EPA authorizes regulatory policy broadly for the United States but is not immune to legal challenges from individual states. In some cases, the U.S. judicial system is used to delay or block implementation and subsequent enforcement. Both the UN and Minamata ultimately depend on member nations and ratifying countries respectively to legislatively implement agreed upon policies and terms as well as provide enforcement, both of which are outside the authority of these international bodies. Without nationally implemented legislation that legally obligates each respective country to comply to the terms of global treaties or international initiatives, policies are difficult if not impossible to enforce within said countries.

Regulatory bodies are incredibly serious about eliminating all use of mercury and will likely get stricter with each passing year. Policy, however, generally includes language regarding the intention that complete and immediate bans of mercury are not meant to result in the destruction or undermining of the economy as well as entire industries operating responsibly within the global community. Lobbying groups for various industries that use elemental mercury or mercury compounds in various manufacturing processes or mercury-added products routinely advocate longer phase-out periods. As a result, adopted policy, including that of the Minamata Convention on Mercury, permits exemptions and phase-out extensions that are periodically reviewed and further extended as needed. The onus, however, is on countries, companies, and industries to make the case and apply for exemptions which are granted at the discretion of each regulatory body for a predetermined number of years. Expiring exemptions must be resubmitted for renewal consideration and extension approval.

While eliminating industrial anthropogenic mercury is a laudable goal that is hopefully achieved someday, many challenges face regulatory agencies as well as manufacturers that produce or use products containing mercury. This includes navigating and interpreting the broad legislative language and requirements mandated by all regulating bodies and nations; achieving local and global compliance; identifying, developing, proving, and adopting suitable alternatives; comprehending and implementing phase-out and phase-down timelines; seeking extensions for products and processes where alternatives are inferior, are not practical, are unaffordable, or result in other highly negative and unintended consequences of use; and the time and resources required to submit, review, and process extension requests.

Other challenges include identifying and holding the biggest offenders and polluters responsible, many of whom, such as miners of cinnabar ore, black market distillers of elemental mercury, and artisanal gold miners, are engaging in economic activity that currently violates or will soon violate Minamata Convention agreements. While some individuals participate in these practices solely for profit, others such as ASGM miners reside in communities where income generating opportunities are limited. To many ASGM miners, the use of mercury is a matter of survival, and most continue to labor in gold mines even when aware of mercury's toxicity.

12. Minamata Convention on Mercury and its Requirements

The ultimate goal of the Minamata Convention on Mercury is to eliminate all global anthropogenic mercury use. That part is clear. The means and timeline of implementation across all industries that utilize mercury in all its forms, however, are not so clear. This is because exemptions are allowed in the absence of viable mercury-free alternatives, and international treaties are entirely dependent on how ratifying parties institute and enforce compliant legislation within their own territorial boundaries. Once implemented, the primary recourse against parties in violation is economic sanctions.

In terms of global policy regarding mercury use, the Minamata Convention on Mercury has the most aggressive targets. This includes a broad mandated ban on the production, import, and export of mercury-added products as outlined in the treaty agreement with an effective date of 1 January 2020. Phase-out and phase-down timelines as well as products and processes that have been given temporary extensions of use are detailed in Annexes A and B of the treaty. UV curing lamps are not specifically addressed.

The UN recognizes 193 countries as member states. 137 countries have ratified the Minamata Convention on Mercury. As a result, most manufactures and end users fall under the mercury ban. As previously noted, however, the requirements of the Minamata Convention must be implemented and enforced at national levels by each ratifying party, and each and every party is still trying to determine how best to proceed as well as the practical implications on its citizens by doing so. Effectively, companies that produce, sell, or use mercury-added products globally are faced with researching and understanding the current and ever-evolving mercury legislation in any of the 137 ratifying countries where they do business.

Key aspects of the Minamata Convention as documented in the *Minamata Convention on Mercury Text and Annexes*[18] include the following:

- **Article 4: Mercury-added products** states that *Each Party shall not allow, by taking appropriate measures, the manufacture, import or export of mercury-added products listed in Part I of Annex A after the phase-out date specified for those products, except where an exclusion is specified in Annex A or the Party has a registered exemption pursuant to Article 6.*

- **Article 6: Exemptions available to a Party upon request** states that *exemptions are available to a Party upon request. Any State or regional economic integration organization may register for one or more exemptions from the phase-out dates listed in Annex A and Annex B, hereafter referred to as the "exemption", by notifying the Secretariat in writing.*

- **Annex A: Mercury-added products** states *the following are exempt.*
  - *Products essential for civil protection and military use.*
  - *Products for research, calibration of instrumentation, for use as reference standards.*

- *Where no feasible mercury-free alternative for replacement is available, switches and relays, cold cathode fluorescent lamps and external electrode fluorescent lamps (CCFL and EEFL) for electronic displays and measuring devices.*
- *Products used in traditional or religious practices, and*
- *Vaccines containing thiomersal as preservatives.*

- **Article 17: Information exchange**, paragraph 1 (c) (I) specifies that *Each Party shall facilitate the exchange of…information on technically and economically viable alternatives to mercury-added products.*

- **Article 18: Public information, awareness and education**, paragraph 1 (a) (iii) states that *Each Party shall promote and facilitate…provision to the public of available information on…(mercury-added products).*

- **Article 21: Reporting**, paragraph 1 states that *Each Party shall report to the Conference of the Parties (COP)…on the measures it has taken to implement the provisions. First reports are due December 2021.*

With each meeting of the Minamata Convention's Congress of the Parties (COP), new policy will be adopted, and phase-out and phase-down timelines clarified. The fourth meeting of the COP took place in Indonesia from 21 to 25 March 2022. During this meeting, phase-out timelines for eight mercury added products and a phase-down timeline for dental amalgam used in patients under 15 years of age as well as pregnant and breastfeeding women was adopted.[15] It does not appear that UV curing lamps were specifically addressed; however, details of the meeting are still being published. The fifth meeting of the COP is scheduled for 30 October to 3 November 2023 in Geneva, Switzerland.[19]

13. Impact of Regulation on Global Supply and Trade

According to UN Environment, five main sources of elemental mercury supply global manufacturing and precious metals mining processes.[12] These include:

- **primary mining** and processing of cinnabar
- **by-products** of non-ferrous mining operations and oil and gas refining
- **recovered mercury** from decommissioned chlor-alkali facilities and waste
- **spent mercury** from mercury-added products recycling
- **reserves** held by governments and private entities

As of 2022, primary mining occurs in China, Mexico, Indonesia, and the Krygyz Republic.[12] The Krygyz Republic, located in central Asia, is more commonly known as Kyrgyzstan or Kirghizia. While cinnabar has been mined in numerous other countries, all mines have closed or are no longer officially in operation. Despite the EU and the U.S. exiting cinnabar mining, other sources of elemental mercury furnish both regions with ample supplies.

On 22 October 2008, the European Union banned the export of metallic mercury, cinnabar ore, mercury (I) chloride or calomel (Hg_2Cl_2), mercury (II) oxide (HgO), and mixtures of metallic mercury with other substances including alloys of mercury with a mercury concentration of at least 95% by weight. The ban became effective 15 March 2011.[20] On 14 October 2008, the US adopted legislation that banned the export of metallic mercury beginning 1 January 2013.[21] On 17 May 2017, the EU updated and replaced its 2008 export ban with additional legislation that aligned the EU with the Minamata Convention terms and banned the export of mercury sulfide (HgS) distinct from cinnabar ore, mercury (II) sulphate ($HgSO_4$), and mercury (II) nitrate ($Hg(NO_3)_2$).[22] Beginning 1 January 2020, the U.S. implemented an expanded export ban to include mercury(I) chloride or calomel (Hg_2Cl_2), mercury(II) oxide (HgO), mercury(II) sulfate ($HgSO_4$), mercury(II) nitrate ($Hg(NO_3)_2$), and cinnabar or mercury sulphide (HgS).[23]

Figure 11: Minamata Convention on Mercury permits active cinnabar mines to operate until 2032.

Bans on specific compounds better accommodate the terms and goals of Minamata by making it more difficult for individuals and companies to circumvent the 2008 EU and U.S. bans on elemental mercury exports. This occurs when mercury compounds are exported solely for the purpose of extracting elemental mercury from the compounds once they arrive in the country of import. It should be noted that mercury export bans do not apply to mercury-added products such as UV curing lamps.

The impact of the EU and U.S. export bans on mercury are that manufacturers of mercury-added products and users of mercury in industrial processes are restricted to domestic sources of elemental mercury and sourcing from a shrinking number of international exporters whose shipments are closely monitored and tracked by UN Environment and its Comtrade database. In cases where regional or domestic demand exceeds supply, such as for ASGM workers, illegally sourced elemental mercury is increasingly obtained on the black market.

Prior to the export bans, the EU and the U.S. served as the international trading hubs for elemental mercury. During that time, all mercury recycled and recovered in the EU and the U.S. which was not used domestically was available for sale on the international market.[12] Following the export bans, Hong Kong and Singapore became the main trading centers handling a significantly reduced global supply with Turkey and Vietnam serving as storage and transit centers.[12]

Due to export bans and shifts in production of many mercury-added products to Asia, the EU and the U.S. are both experiencing strong domestic elemental mercury surpluses coupled with falling demand from domestic buyers.[12] These conditions exert downward pressure on mercury prices in these regions.

Simultaneously, increased demand from countries blocked from accessing EU and U.S. supplies has driven international pricing of elemental mercury to historic highs.[12]

In 1994, none of Mexico's 300 known cinnabar mines were officially in operation.[12] During the 1990s and 2000s, prior to the 2008 EU and U.S. export bans, mercury mining was not economically viable in Mexico.[12] As a consequence of the export bans, Mexico resurrected several mines, and Indonesia and China increased primary mining activities.[12] This is occurring despite Minamata Convention requirements that all 137 ratifying countries prohibit development of new primary mercury mines that were not in operation when the Minamata Convention entered into force (2017) and that all cinnabar mines in operation in 2017 must be phased out within 15 years (2032).

The Minamata Convention specifically prohibits the sale of primary mercury to ASGMs. As a result, miners struggling to procure mercury from regulated industrial channels must obtain it from a shrinking number of domestic and international sources willing to trade against the terms of the treaty. Unfortunately, decreasing supply and bans on international shipments of elemental mercury as well as record-high gold prices drive black market distillation from cinnabar in less developed areas of the world. This mix of circumstances has contributed to Indonesia becoming the largest producer and largest international shipper of elemental mercury. Most of this mercury is illegally mined, unsafely distilled, transported in shoddy and unregulated packaging, and regularly shipped with fraudulent or missing documentation.[12,24]

Since 2005, more than 60% of the total global demand for elemental mercury is driven by ASGMs in Africa, Asia, and Latin America and vinyl chloride monomer (VCM) producers in China.[12] According to UN Environment, increasing use by these two sectors outpaces all reductions achieved by shifting mercury-added products to other viable alternatives. As a result, current demand for mercury outside the EU and the U.S. exceeds available supplies.[12] The direct implication is rising global prices outside the EU and the U.S. This incentivizes further mining of cinnabar, more elemental mercury distillation from cinnabar, and illegal international shipments; all of which increases global inventories.

During the last half century, regulatory organizations have increased awareness of the ill-effects of mercury use and promoted the need to reduce global reliance on mercury in products and processes wherever possible. This has contributed to a net decrease in total regulated global imports and exports of elemental mercury.[12] Ongoing innovation of viable mercury substitutes has also decreased overall mercury demand for use in mercury-added products and processes.[12] Unfortunately, restricted free-market access to supplies located in the EU and the U.S. has simultaneously led to increased cinnabar mining in China, Mexico, and Indonesia and a net increase in total global mercury inventories.[12]

14. Benefits of UV Curing in Manufacturing Processes

Since the 1950s, UV curing systems containing mercury vapor lamps have been increasingly integrated into numerous manufacturing processes. UV curing is highly beneficial to manufacturers as it provides a means of efficiently and instantly transforming liquid-like inks, coatings, adhesives, extrusions, and other photopolymers that are wet-to-the-touch into chemically crosslinked solids that are either dry-to-the-touch or intentionally tacky as with pressure sensitive adhesives. When products are UV cured, a rapid chemical reaction renders the goods immediately ready for use, further processing, and shipping.

UV curing not only saves valuable production time it also reduces manufacturing floor space, results in less heat transfer to manufactured products, and is more environmentally friendly than solvent-borne and many water-borne processes that require energy consuming thermal dryers or ovens. In the case of solvent-borne processes, emissions permits and after-burners or oxidizers are also typically required. As a result, UV curing technology is widely used in commercial printing, label and package converting, direct to product decoration, polymer extrusion, flexo plate and screen making, and industrial coating, converting, and finishing.

UV curing offers manufacturers the following process and environmental benefits:

- elimination of solvent containing chemistry; energy consuming thermal ovens, after-burners, and oxidizers; and greenhouse gasses including Volatile Organic Compounds (VOCs) and Hazardous Air Pollutants (HAPs)
- reduction in required manufacturing space, energy consumption, and carbon footprint
- ability to enable high-speed production processes due to the nearly instant molecular reaction of UV chemistry when exposed to ultraviolet energy
- ability to adhere UV cured formulations to a wide range of materials
- ability to produce bold and vibrant colors
- ability to provide robust chemical, scratch, and mar resistance
- ability to ship and/or finish products immediately following cure
- final product performance and aesthetic properties that exceed those obtained with water-based formulations and exceed or are comparable or acceptable to solvent-based formulations

15. Mercury's Function in UV Curing Lamps

A discrete amount of elemental mercury is necessary for mercury vapor gas discharge lamps to function. Without mercury, UV curing lamps do not work. This is because the physics of elemental mercury results in emissions of ultraviolet, visible, and infrared light when mercury is vaporized into a high-temperature plasma within a sealed, inert gas-filled quartz tube under medium pressure. No other discharge material produces the same spectral output as mercury. For 75 years, UV curable chemistry has been intentionally formulated to react to the broad-spectrum output generated only by vaporized elemental mercury.

Mercury vapor lamps include both electrode arc lamps, shown in Figure 12, and microwave lamps. The mercury inside arc lamps is energized by a high voltage arc; whereas, mercury inside microwave lamps is energized by microwave generating magnetrons inside the lamphead assembly. Both lamp types are also available in metal halide variations also known as additive and doped. Metal halide, doped, and additive lamps all contain mercury.

Figure 12: Electrode Arc Lamp.

During transport, storage, and use, mercury and its vapor are completely and safely contained within the sealed structure of the gas discharge lamp. Only thermal energy and electromagnetic wavelengths of UV, visible, and infrared energy are transmitted through the quartz tube barrier when a lamp is powered. If the quartz wall is pierced in any way or if the lamp seal becomes damaged, the internal pressure of the lamp adjusts to atmospheric pressure, and the inert gases escape to the environment. When this happens, the lamp immediately ceases to work, and due to mercury's low volatility, the mercury content subsequently condenses on internal lamp components or external surfaces while some mercury potentially vaporizes to the air.

16. Mercury Content in Lamps and Other Products

The discrete amount of elemental mercury contained inside medium pressure UV curing lamps varies across designs and lamp lengths; however, it is typically between 10 and 100 mg per lamp. On rare occasions and for special lamps, it can be more than 100 mg. To account for the range of values in inventory estimates, UN Environment uses an average value of 25 mg per UV lamp.[3] For reference, one milligram is equivalent to 0.000035274 ounces.

Fluorescent tubes, which developed in the 1930s and are still widely used in residential, commercial, and public buildings, contain around 5 mg of mercury per lamp.[25] Compact fluorescents (CFLs), which commercialized in the mid-1980s, were initially made with 5 mg of mercury per lamp.[25] The amount of mercury in CFLs has since been reduced to between 2.5 and 3.5 mg per lamp,[25] and certain spiral versions contain as little as 0.8 to 0.9 mg.[25] According to a 2007 article in Popular Mechanics, *5 mg of mercury is just enough to cover a ballpoint pen tip*.[26]

In relation to other mercury-added products and processes, most lighting technology contains relatively low levels of mercury. For perspective, dental amalgam uses as much as 1 g of elemental mercury per filling,[11] and older and already discontinued medical devices such as esophageal dilators (bougies), feeding tubes, and gastrointestinal tubes that used mercury as a weight to aid insertion into the body contained as much as 1 kg.[27] Sterile water and tungsten are now used instead of mercury in these devices. Miners in ASGMs who practice concentration amalgamation require 1.3 grams of mercury for every gram of gold recovered.[12] Whole ore amalgamation requires 5 grams of mercury on average for every gram of gold recovered but can use as much as 20 grams of mercury per gram of gold.[12] Mercury fever thermometers including oral, rectal, and baby variations contain around 610 mg.[28] More sensitive basal temperature thermometers that track very minute changes in body temperature contain 2.25 grams of mercury,[28] and mercury incorporated into now discontinued electrical relays and switches sold between 2001 and 2007, some of which are still in use, ranges anywhere from 10 mg to 153 grams per device.[29] In several cases, numerous relays were integrated into larger assemblies where the combined mercury total for the entire relay unit could be as much as 400 grams.[29]

A summary of mercury content utilized in various mercury-added products and processes is provided in Figure 13. For perspective, a comparison of mercury content found in oral thermometers and dental amalgam as compared to mercury vapor lamps is shown in Figure 14.

Product	Mercury Content[1]	Product	Mercury Content[1]
spiral CFLs	0.8 – 0.9 mg	dental amalgam	500 – 1000 mg
CFLs	2.5 – 3.5 mg	ASGM (concentration)	1.3 grams / gram gold
fluorescent tubes	~5 mg	ASGM (whole ore)	5 grams / gram gold typ
low pressure germicidal	5 – 15 mg	ASGM (whole ore)	20 grams / gram gold
medium pressure UV	10 – 100 mg[2,3]	elec relays and switches[4]	10 mg – 153 grams
fever thermometer – oral	~610 mg	medical devices[5] (esophageal dilators, feeding and gastro tubes)	up to 1 kg
fever thermometer - basal	~2250 mg		

[1]5 mg of mercury covers a ballpoint pen tip [2]UN uses 25 mg for inventory estimates [3]special UV lamps can be higher [4]market restrictions [5]discontinued

Figure 13: Mercury content utilized in various mercury-added products and processes.

Figure 14: There is 610 mg of elemental mercury in a typical fever thermometer. This is 6 to 60 times greater than the typical range of mercury vapor curing lamps. There is 800 mg of elemental mercury on average in a single dental filling. This is 8 to 80 times greater than the typical range of mercury vapor curing lamps.

17. Safety of Mercury Vapor Lamps

When reputable UV lamp manufacturers source elemental mercury from non-mining sources such as exiting reserves and byproducts of other processes such as oil and gas refining, the production of UV curing lamps does not contribute to increases in global mercury inventories. Reputable lamp manufacturers also implement safety and quality protocols that protect employees during manufacturing processes and ensure all mercury is safely and securely contained within the lamp prior to shipment, during normal shipment, and with proper use. This is typically overseen by internal staff and guided by standards developed by environmental and occupational regulatory and enforcement authorities within the respective country of manufacture with some guidance by industry trade groups.

When purchasing from qualified lamp suppliers, many of whom continue to manufacture lamps in the UK, the EU, and the U.S., integrators, OEM machine builders, and end users should always receive sealed and tested lamps in proper packaging. Lamps that are not sourced from reputable suppliers, properly packaged, and clearly marked by the manufacturer should not be used. In many cases, aftermarket lamps void UV curing system warranties, compromise the integrity of the system, and negatively affect curing performance and lamp life. At the location of intended use, lamps are securely installed within lamphead assemblies which are then installed in larger manufacturing systems. Users are advised to recycle spent lamps through recycling centers capable of safely recovering mercury or transporting lamps to dedicated facilities with appropriate recovery equipment.

On the rare occasion that a mercury vapor lamp breaks, clean-up procedures established for all types of mercury-added gas discharge lamps should be followed. Environmental and occupational regulatory agencies, such as the U.S. EPA, routinely publish recommended procedures for more commonly used fluorescent and compact fluorescent lamps on their websites: https://www.epa.gov/cfl/cleaning-broken-cfl#qi. According to the European Commission, *the amount of mercury in the air after a compact fluorescent lamp breaks is relatively high initially but is not enough to cause harm. The released mercury vapour turns quickly into a liquid and the level of mercury in the air decreases very rapidly so it is unlikely that broken CFLs pose any risk to the health of adults.*[30]

The Scientific Committee on Health and Environmental Risks (SCHER) is one of three independent non-food scientific committees that advise the European Commission on matters of consumer safety, public health, and the environment. According to a SCHER Report from 2010,

> *A fluorescent light bulb contains 5 mg of Hg. Assuming release of the total Hg-content of a lamp after breakage into an average room, Hg concentrations in the range of or above occupational exposure limits (100 µg/m^3) can be derived. These concentrations are also well above regulatory limits for Hg in a general environment. Regarding environmental exposures, the US EPA has defined a reference concentration (RfC) of 300 ng/m^3, and the US CDC derived a maximum residue limit (MRL) of 200 ng/m^3. However, it needs to be recognized that these concentrations are applied to life-long inhalation exposures, are based on conservative extrapolations, and are considered protective for all groups of the population, including potentially sensitive subgroups. The US EPA also has defined an acute RfC of 1.8 µg/m^3 for Hg. The acute RfC is an estimate (with uncertainty spanning an order of magnitude) of an acute continuous inhalation exposure (time weighted average with a duration up to 24 hours) without appreciable risks of deleterious effects during a lifetime for the human population also including sensitive subgroups*.[30]
>
> *The simple assumption of a complete evaporation of the Hg content from a broken light bulb apparently results in a wide overestimation of air concentrations of Hg over time. Indeed, most of the released Hg may re-condense, due to the low volatility of Hg. Measured data suggest that a broken CFL may produce Hg concentrations of 8 to 20 µg Hg/m^3 for a short time after the breakage. Air concentrations rapidly decline: concentrations ≤2 µg Hg/m^3 have been measured in a house two days after an Hg spill from a CFL. An experimental study indicates even lower concentrations, between 0.8 ng/m^3 $Hg^0$and 0.1 µg/m3 Hg^0, depending on CFL lamp type, in a room after CFL-breakage.*[30]

18. Recycling Mercury

Due to careful construction, manufacturing, packaging, shipping, and use of mercury lamps as previously described and the fact that most manufactures source mercury from sources that do not include primary mining, mercury releases to the environment from UV curing lamps mainly occur through improper waste disposal.[3] As a result, when mercury discharge lamps reach the end of useful life, they should always be recycled using a qualified lamp or electronics recycling center that ensures lamp components are separated and spent mercury is safely and securely captured. Reclaimed mercury goes into long-term secure storage, permanent disposal, or is processed through established and documented protocols that safely re-introduce elemental mercury into permissible manufacturing channels.

Since emissions to air and releases to water from mercury-added products such as lamps, batteries, and dental amalgams largely occur during waste disposal,[3] these items should never be discarded with bulk trash collection. This includes industrial UV curing lamps as well as commercial and residential fluorescent and CFL lamps. When discarded with general trash, mercury inside lamps is exposed to the biosphere when items are crushed. The mercury from crushed lamps is emitted to the air during incineration, released to wastewater during processing, or buried in mixed-waste landfills. Mercury in landfills can sometimes migrate into groundwater or be emitted to the air. Fortunately, mercury pollution from UV curing systems is avoidable when established mercury vapor lamp recycling procedures are properly and routinely followed.

Most mercury recycling occurs in China, the EU, the U.S., and India.[12] Prior to the EU and U.S. mercury export bans, recycling fees were offset by the potential value of all recovered mercury that could be resold into the global market. As domestic mercury demand in the EU and the U.S. has been significantly reduced in recent years and exports are no longer permitted, the economic value of mercury recycling has declined in these regions. Consequently, this has driven up the cost of recycling. Nevertheless, as companies become increasingly committed to sustainability in manufacturing operations, all mercury-added waste products should be recycled with the cost of recycling treated as a cost of operations. While it varies by country and recycling center as well as size and type of lamp, typical recycling charges per UV lamp can be estimated at £15, €20, and $25 or higher. Users are encouraged to consult local recycling centers for more accurate figures as recycling charges vary widely and all economies are currently experiencing inflation.

Figure 15: Spent UV curing lamps should always be recycled through qualified recycling centers.

19. Permanently Disposing Mercury

As a result of decreased mercury demand in the UK, the EU, and the U.S., recycled and recovered mercury in these regions will be increasingly diverted to permanent disposal.[12] In order to safely dispose elemental mercury, it must first be isolated and stabilized. Stabilization occurs through either wet or dry processes that convert elemental mercury into insoluble inorganic mercury (II) sulfide (HgS) which is the chemical make-up of cinnabar. The synthesized compound is then securely stored in underground salt mines no longer in use or in special landfills. Figure 16 provides an image of a non-specific underground mine. As an additional precaution, the mercury (II) sulfide is sometimes mixed with a special cement before deposit. The development of safe and permanent mercury disposal practices is an ongoing effort not yet standardized or universally adopted.

As provisions of the Minamata Convention are increasingly implemented at national levels, more and more recycled mercury as well as mercury recovered from by-products and decommissioned manufacturing processes will be removed from circulation and permanently disposed. In the meantime, many companies are holding mercury onsite in long term storage containers as this is currently less costly than permanent disposal.[12]

Figure 16: Once elemental mercury is stabilized by conversion to mercuric sulfide (HgS), it can be permanently disposed in designated salt mines (non-specific mine shown) or special landfills.

20. Impact of Mercury Regulation on UV Curing Industry

This is a summary of how mercury regulatory policy is impacting medium-pressure, mercury vapor UV curing lamps as of March 2022. This information is sourced from publicly available documents that address restrictions on sale, shipment, and use of mercury by REACH, RoHS, TSCA/Lautenberg Act, and Minamata. Under no circumstances should this summary be considered legal advice. While readers can use this document as a guide, they are encouraged to refer directly to cited sources, conduct additional research as needed, and monitor the situation periodically in order to form their own assessment of the situation.

UV Lamp Production, Shipment, and Use

Domestic and international shipments of mercury vapor lamps used in UV curing processes and containing sealed elemental mercury are permitted. There are currently no known provisions in any country worldwide that specifically ban mercury UV curing lamps from production, use, export, import, or general shipment. Furthermore, no new restrictions specifically addressing mercury vapor UV curing lamps are anticipated in the near term. Policy is constantly evolving, however, and varies by country. As a result, readers are encouraged to review the latest requirements documented on regulatory websites, pay attention to industry briefings issued by professional organizations, and periodically consult suppliers of UV curing lamps and equipment.

EU REACH Restrictions

REACH is an EU Directive that focuses on the *registration, evaluation, authorisation and restriction of chemicals* produced, used, and sold in the EU. Its directives and policies apply to items manufactured with chemicals and intended for use by the public as well as professional, commercial, and industrial entities. In addition, REACH publishes a list of *substances of very high concern* (SVHC). Any material on the SVHC list, which includes mercury, is meant to be phased out and replaced with safer alternatives. In certain cases, REACH restricts or completely bans the use of some chemicals. The European Commission partners with the European Chemicals Agency (ECHA) and member nations to implement and enforce REACH requirements.[32,33]

REACH directives restrict mercury containing fever thermometers, barometers, hygrometers, manometers, sphygmomanometers, strain gauges used with plethysmographs, tensiometers, thermometers and other non-electrical thermometric applications, pycnometers, and mercury metering devices for determination of the softening point from *being placed on the market*.[34] As of March 2022, there are no REACH restrictions on medium pressure mercury vapor lamps or published phase-out dates.

REACH Market Restrictions

items in this list cannot be placed on the European market

fever thermometers	sphygmomanometers
barometers	pycnometers
hygrometers	some strain gauges
manometers	metering devices for softening point

Figure 17: REACH market strictions for mercury-added products within the European Union.[34]

EU RoHS Restrictions

RoHS is an EU Directive that regulates the use of hazardous substances in *electrical and electronic equipment* (EEE) as well as the subsequent *waste stream of electrical and electronic equipment* (WEEE).[35] RoHS applies to all items manufactured for use in the EU and items manufactured elsewhere and imported to the EU. There have been two versions of the RoHS Directive since inception: RoHS 1 and RoHS 2. RoHS 2 ultimately replaced RoHS 1.[36] The categories of EEE covered under RoHS 2 are provided in Annex I of the Directive. Medium pressure mercury arc lamps are classified in Annex I as *Category 5 Lighting Equipment*.[39]

The original 2003 legislation, Directive 2002/95/EC,[37] restricted 6 substances and mandated RoHS compliance for all applicable products in the EU beginning 1 July 2006. It was amended in 2008,[38] replaced with Directive 2011/65/EU in 2011 and repealed in 2013. The 2011 replacement is known as RoHS-Recast or RoHS 2.[39] RoHS 2 added a CE-marking requirement and called for additional recordkeeping requirements. Directive 2015/863[40] added four phthalates restrictions and mandated a compliance deadline of 22 July 2019. RoHS 2 was amended in 2017 and again in 2021.[41,42,43]

Article 4(1) of RoHS 2 directs *Member States shall ensure that EEE placed on the market, including cables and spare parts for its repair, its reuse, updating of its functionalities or upgrading of its capacity, does not contain the substances listed in Annex II.*[39] The following ten substances of very high concern (SVHC) are listed in the RoHS 2 Directive under Annex II. The Directive restricts all manufactured EEE products from exceeding specified maximum concentration values for these substances as specified in the Annex.[39,40]

- Lead (Pb)
- Mercury (Hg)
- Cadmium (Cd)
- Hexavalent chromium (Cr 6+)
- Polybrominated biphenyls (PBB)
- Polybrominated diphenyl ether (PBDE)

- Bis (2-ethylhexyl) phthalate (DEHP)
- Butyl benzyl phthalate (BBP)
- Dibutyl phthalate (DBP)
- Diisobutyl phthalate (DIBP)

Conventional medium pressure mercury vapor lamps used in UV curing applications contain over 10 mg of mercury and subsequently fall under the regulatory requirements of RoHS 2 and the concentration limits of Annex II. Since 3 Jan 2013, electrical and electronic devices sold into the European market are restricted to a maximum concentration value tolerated by weight in homogeneous materials. For mercury-added products, this value cannot exceed 0.1% by weight.

Despite the listing of mercury in Annex II, RoHS 2 legislation historically contains a scope carve-out that has always been applied to UV curing systems. This portion of the legislation stipulates that all manufactured goods not within scope of RoHS are automatically exempt. The scope or RoHS 2 excludes *large-scale stationary industrial tools* (LSSITs) and *large-scale fixed installations* (LSFIs).[39] LSSITs are defined as *a large-scale assembly of machines, equipment, and/or components, functioning together for a specific application, permanently installed and de-installed by professionals at a given place, and used and maintained by professionals in an industrial manufacturing facility or research and development facility.*[39] LSFIs are defined as *a large-scale combination of several types of apparatus and, where applicable, other devices, which are assembled and installed by professionals, intended to be used permanently in a pre-defined and dedicated location, and de-installed by professionals*.[39]

UV curing systems and the equipment in which they are installed such as printing presses, industrial curing chambers and tunnels, and converting lines among others are heavy, require on-site assembly and installation, operate off high-voltage main AC power connections, and are not easily moved once integrated into production processes. As a result, the use of mercury UV curing systems in most production applications is generally understood to be exempt from RoHS restrictions indefinitely due to scope regardless of any specific ban on mercury UV curing lamps. Spare parts and upgrades to UV curing system installations made before any imposed ban are allowed indefinitely.

Annex III of RoHS 2 lists approved exemptions to Article 4(1) as well as corresponding scope and dates of applicability.[39] With respect to UV lamps, the following exemptions apply.

- **4(a):** mercury in other low pressure discharge lamps; no limitation of use until 31 December 2011; 15 mg may be used per lamp after 31 December 2011
- **4(f):** mercury in other discharge lamps for special purposes not specifically mentioned in this Annex

Low-pressure discharge lamps referenced in 4(a) include UV lamps used for sterilization, disinfection, and purification. Since medium-pressure electrode arc and microwave UV curing lamps are not specifically addressed anywhere else in RoHS 2, it has generally been understood that 4(f) applies to all mercury vapor gas discharge lamps used for UV curing as well as other disinfection, sterilization, and disinfection processes not covered by the lamps in 4(a). RoHS 2 Annex III 4(f) does not stipulate any limits regarding mercury use or require phase-out timelines. As a result, medium pressure mercury vapor lamps have always been understood to be exempt from RoHS.

Article 5 of the RoHS Directive allows the European Commission to periodically review all exemptions listed in Annex III. Upon review, existing exemptions can be renewed, revoked, or further clarified by creating new categories or subcategories. The specific verbiage that guides this process is as follows:

> *Article 5 of the Directive provides for the adaptation of Annexes III and IV to scientific and technical progress, which can include granting, renewing and revoking of exemptions. Pursuant to Article 5(1)(a), exemptions are to be included in Annexes III and IV only if such inclusion does not weaken the environmental and health protection afforded by Regulation (EC) No 1907/2006 (REACH) and where any of the following conditions is fulfilled: (i) their elimination or substitution via design changes or materials and components which do not require any of the materials or substances listed in Annex II is scientifically or technically impracticable; (ii) the reliability of substitutes is not ensured; (iii) the total negative environmental, health and consumer safety impacts caused by substitution are likely to outweigh the total environmental, health and consumer safety benefits thereof.*[42,43]
>
> *Decisions on exemptions, and their duration, must also take into account the availability of substitutes and the socioeconomic impact of substitution. Decisions on the duration of exemptions must also take into account any potential impact on innovation. Life-cycle thinking on the overall impacts of the exemption must be applied, where relevant.*[42,43]

An evaluation of exemptions for the mercury-added products covered under 4(a) and 4(f) in Annex III occurred in 2015/16 and again in 2020/21. Both times, Bio Innovation Service, UNITAR, and Fraunhofer IZM were appointed by the European Commission to serve as the committee overseeing the review and evaluation process and make recommendations to the EC. Exemption Request Forms to petition the continued use of mercury were submitted by VDMA and Lighting Europe on behalf of their members for the 2015/16 and 2020/21 RoHS reviews.[44,45,46,47]

VDMA is a German-based European organization with more than 3,300 members. It considers itself *the largest network organisation and important voice for mechanical engineering in Germany and Europe. The association represents the common economic, technical, and scientific interests of this unique and diverse industry*. Additional information can be found on their website: www.vdma.org. LightingEurope regards itself the *voice of the lighting industry*. The organization is based in Brussels and represents 30 individual companies and various national associations that total 1,000 plus European companies. Additional information can be found on their website: www.lightingeurope.org.

The most recent VDMA and LightingEurope applications were made available for public comment until 27 May 2021. Numerous companies submitted comments to the committee. Professional organizations and companies who manufacture or use UV curing sources in production processes also submitted letters and other documents supporting the applications. Following the comment period, Bio Innovation Service, UNITAR, and Fraunhofer IZM drafted recommended changes to RoHS 2 and Annex III for 4(a) and 4(f) and submitted them to the European Commission for review.[48,49,50,51] The EC followed the committee's recommendations, and official Commission Delegated Directives amending Annex III to include additional sub-categories with exemption extensions as noted below were finalized for 4(a) and 4(f) and adopted by the EC on 13 December 2021. [42,43,52,53]

The Commission Delegated Directive, C(2021) 8951, specifically addressing 4(a) highlights the following committee findings in its Explanatory Memorandum. [42]

- *the lamps covered by this exemption are not phosphor-coated and produce mainly light in ultraviolet spectrum. They are installed in equipment for industrial, commercial and residential applications and cover uses such as ultraviolet germicidal or bacterial disinfection/purification of air/water/surfaces;*

- *in order to fulfil these purposes, the light output must be in the deep ultraviolet range. Mercury-free alternatives do not yet provide the necessary wavelength range. Therefore, substitutes with a comparable performance are currently technically impracticable;*

- *it was also concluded that first alternatives coming on the market would not cover the full product range and, at the system level, time is still needed to develop sufficient alternatives, reason for which it was recommended to renew the exemption for the maximum duration of a further five years;*

- *the current scope of the exemption can be narrowed to low-pressure discharge lamps that are not phosphor-coated and emit light in the ultraviolet range.*

- *In conclusion, the scientific and technical assessments, including stakeholder consultations, detailed that, as reliable substitutes are not yet available, the exemption criteria continue to be met with regard to exemption 4(a).*

- *The evaluation results also show that the specific exemption would not weaken the environmental and health protection afforded by the REACH Regulation, in accordance with Article 5 of Directive 2011/65/EU.*

The Commission Delegated Directive, C(2021) 8979, specifically addressing 4(f) highlights the following committee findings in its Explanatory Memorandum.[43]

- *The exemption covers a wide array of applications such as multiple types of ultraviolet lamps (e.g. curing lamps, lamps used in photochemistry, development of polymers), projector lamps, horticultural lamps etc.*

- *Mercury-free substitutes are understood to be available at system level (for use in new light emitting diode (LED) luminaires), but such substitutes have various limitations and cannot be used in the numerous types of existing discharge lamps for special purposes (component replacement).*

- *Currently, the substitution of mercury in the applications concerned is technically impracticable and the current exemption should be renewed. However, where possible, the applications should be further specified. For part of the exemption, it is already possible to specify in further detail the applications where mercury cannot be substituted. For those, the maximum validity for the exemption should apply. The previous formulation of the exemption regarding 'other discharge lamps for special purposes not specifically mentioned' is still necessary for the uses not covered by the specific formulation, but it should be extended for a period shorter than the maximum five years given the prospects of limiting the exemption in future.*

- *In conclusion, the scientific and technical assessments, including stakeholder consultations, detailed that the exemption criteria continue to be met with regard to exemption 4(f), as reworded, as reliable substitutes are not yet available. The evaluation results also showed that renewing the exemption would not weaken the level of environmental and health protection afforded by the REACH Regulation, in accordance with Article 5 of Directive 2011/65/EU.*

The amendments to Annex III include three and five-year exemption extensions as noted below for 4(a) and 4(f). They also add a product subcategory to 4(a) and expand 4(f) into four distinct product categories. The new category that applies to lamps used in UV curing is 4(f) -IV and includes a five-year exemption period expiring at the end of 2026. At which time, mercury lamps emitting light in the ultraviolet spectrum will subsequently be re-evaluated for another exemption renewal or revocation. On 13 December 2021, the European Commission followed the committee's recommendations to renew exemptions 4(a) and 4(f) and officially amended Annex III as follows:[52,53]

- **4(a):** mercury in other low pressure discharge lamps (per lamp): 15 mg; **expires 12 months** after the publication of the Delegated Directive in the Official Journal

- **4(a) -I:** mercury in low pressure non-phosphor coated discharge lamps, where the application requires the main range of the lamp-spectral output to be in the ultraviolet spectrum: up to 15 mg mercury may be used per lamp; **expires 5 years** after the publication of the Delegated Directive in the Official Journal

- **4(f) -I:** mercury in other discharge lamps for special purposes not specifically mentioned in this Annex; **expires 3 years** after the publication of the Delegated Directive in the Official Journal

- **4(f) -II:** mercury in high pressure mercury vapor lamps used in projectors where an output ≥2000 lumen ANSI is required; **expires 5 years** after the publication of the Delegated Directive in the Official Journal

- **4(f) -III:** mercury in high pressure sodium vapor lamps used for horticulture lighting; **expires 5 years** after the publication of the Delegated Directive in the Official Journal

- **4(f) -IV:** mercury in lamps emitting light in the ultraviolet spectrum; **expires 5 years** after the publication of the Delegated Directive in the Official Journal

The portion of RoHS legislation that most impacts EU-based users of UV curing technology is the requirement for *environmentally sound recovery and disposal of waste EEE*.[39] This is understood to mean that mercury-added products must be recycled at the end-of-life. Recycling facilities separate mercury from other lamp assembly components and ensure mercury is not incinerated and emitted to the atmosphere, buried in landfills, or released to wastewater. Recycling spent UV lamps is important in that it prevents mercury contained within the lamp from entering the biosphere once the lamp's UV output is no longer sufficient for effective curing.

USA TSCA-EPA Restrictions

The Frank R. Lautenberg Chemical Safety for the 21st Century Act (Lautenberg Act) is legislation enacted by the United States of America on 22 June 2016.[54,55] It amended the 1976 U.S. Toxic Substance Control Act (TSCA).[56] The Lautenberg Act enables mercury compounds to be added to the 2008 U.S. export ban of elemental mercury and gives the EPA authority to determine which mercury compounds apply to the ban. Section 8(b) also requires the EPA to establish *(1) an inventory of mercury supply, use, and trade in the United States and (2) reporting requirements by rule applicable to any person who manufactures mercury or mercury-added products or otherwise intentionally uses mercury in a manufacturing process.*[54]

In compliance, the EPA published a rule in the Federal Register on 27 June 2018 entitled *Mercury; Reporting Requirements for TSCA Mercury Inventory*.[57] The rule requires *persons who manufacture (including import) mercury or mercury-added products, or otherwise intentionally use mercury in a manufacturing process to report usag*e. According to the EPA, reporting is not required for manufactures or importers of assembled products that incorporate mercury-added products.

The EPA reporting deadline for each year under review is July 1. Reported data must include all applicable mercury supply, use, and trade for the calendar year preceding the year in which the deadline occurs. Data can be submitted electronically through the EPA's online Central Data Exchange (CDX) https://cdx.epa.gov under the section Mercury Electronic Reporting (MER). For example, a single entry by persons or organizations required to report had to be submitted prior to 1 July 2019 for calendar year 2018 (January 1 to December 31). The next reporting deadline is 1 July 2022 for the period covering 2021 (January 1 to December 31). The most recent collated inventory report on the supply, use, and trade of mercury in the United States for 2018 was published by the EPA on 30 March 2020. The report, *Inventory of Mercury Supply, Use, and Trade in the United States 2020*, is available for download on the EPA website and is updated every three years.[58]

Reporting of mercury to the EPA is in pounds (lbs). While there are no exclusions for low levels of use, the minimum allowable reporting quantity is 1 lb.[59] At the high-end of lamp content (100 mg), 4,536 UV curing lamps are necessary to achieve 1 lb of mercury as 1 lb is equivalent to 453,592.37 mg. At the low-end of lamp content (10 mg), 45,360 UV curing lamps are necessary to achieve 1 lb of mercury. Even using the 25 mg average mercury content of UV lamps referenced by UN Environment for its inventory estimates would mean that 18,143 UV lamps are needed to accumulate 1 lb of elemental mercury.

While a domestic manufacturer or an importer of mercury vapor lamps meant for sale to other users may turn inventory volumes between 4,536 and 45,360 lamps annually, a typical company importing replacement lamps for use in its UV curing systems probably will not. In fact, it would require nearly 73 ten-station flexo presses, continuously running 5 days a week for 24-hours a day with no interruptions, and consistently changing lamps every 1,000 hours to consume 4,536 lamps in a 52-week year. The same number of lamps containing less than 100 mg would fall significantly short of a pound. Larger companies reporting for multiple plants located in the U.S. may approach the low end of this range but would likely only need to report if they were directly importing replacement lamps as opposed to purchasing lamps from domestically warehoused inventories. Consequently, if the EPA were to achieve majority reporting compliance of all companies importing one or more UV curing lamps, it would lead to significant over-reporting of the quantity of mercury in UV lamps imported to the U.S.

Manufacturers located in the U.S. are strongly encouraged to read the *Compliance Guide Reporting Requirements for the Mercury Inventory of the Toxic Substances Control Act* to determine if it is necessary for themselves or their company to report mercury usage for calendar year 2021 and beyond.[60] If the determination is yes, then a single-entry report must be submitted through the EPA's CDX by 1 July 2022 and every three years thereafter when applicable. For guidance on how to report, refer to the EPA's *Mercury Electronic Reporting System Webinar* available on its website.[61]

It is the EPA's intention that the collected information will enable the U.S. to efficiently update its mercury inventory; better identify manufacturing processes or products that intentionally add mercury; and recommend actions, including proposed revisions of federal law or regulations, to achieve further reductions in mercury use. It should be noted that at the time of this publication (May 2022), the EPA is not making identifications or recommendations and has not currently banned any mercury-added products. This includes UV curing lamps. Another purpose of the reporting and EPA oversight is to facilitate the U.S. Government as it works to achieve its obligations under the Minamata Convention on Mercury.

Minamata Restrictions

In anticipation of wide ranging technical, economical, and practical implications of banning mercury from products and processes, Article 6 of the Minamata Convention on Mercury permits renewable, five-year exemptions that extend phase-out-dates. To be granted an extension, Parties must notify the Secretariat in writing. Annex A also exempts mercury use in products *where no feasible mercury-free alternative for replacement is available*.[18] It should be noted that no phase-out-dates are listed in Annex A for mercury vapor lamps. As a result, Party nations are simply required to phase-out or take measures to reduce mercury in these products when possible.

For comparison, the European Commission is attempting to develop and implement a phase-out plan that would eliminate use of mercury amalgam dental fillings by 2030.[14] In the U.S., there are no active plans to ban or phase-out dental amalgam.[62] As of 24 September 2020, and according to the U.S. Food and Drug Association (FDA) website, the FDA advises against using dental fillings for high-risk groups but does not believe evidence supports a complete ban of dental amalgam. *The weight of the existing evidence does not show that exposure to mercury from dental amalgam leads to adverse health effects in the general population, and its longevity is better than that of alternatives, especially for large restorations…a ban on amalgam may result in deferred or no treatment and have unintended health implications, especially in communities where there might be limited availability of alternative materials.*[62]

On 25 March 2022, during the fourth meeting of the Conference of Parties (COP) of the Minamata Convention on Mercury, an amendment was passed to ban dental amalgam in children under the age of 15 and in pregnant and breastfeeding women. The amendment takes effect 25 December 2022. The UK and the EU are currently compliant as a result of previous legislation. The U.S. is not. As a result, this new amendment will require action by the U.S. Food and Drug Administration (FDA) to maintain compliance with the treaty as well as any other country that has ratified the treaty and is not currently compliant for these specific groups.

The potential for regulatory action as well as growing and vocal public sentiment have a significant impact on corporate decision making. For example, the last publicly traded manufacturer of dental amalgam in the U.S. stopped manufacturing dental amalgam in the third quarter of 2021 due to pressure from 118 environmental, consumer, and children's groups.[15] Densply, the world's largest dental products manufacturer, stopped selling dental amalgam in December of 2020 as a result of an eight-year campaign against amalgam by Consumers for Dental Choice.[15]

While phase-out timelines for medium pressure mercury vapor lamps are not specifically addressed in Annex A of the treaty, banning UV curing lamps faces similar implementation challenges as dental amalgam. This is due to the diverse nature of UV curing and its manufacturing processes as well as the still-evolving nature of LED curing. Provided suppliers and users of UV curing systems are 1) recycling spent mercury vapor lamps, 2) making steady progress in developing alternatives such as UV LED curing, and 3) steadily migrating viable curing applications to LED technology when possible, then ratifying nations are proceeding under the spirit of the Convention, and the terms of the Treaty *appear to be satisfied*.

Article 21 of the Convention requires each Party to provide a national report to the *Conference of the Parties (COP)* that includes, among other information, evidence that demonstrates the Party has met the requirements of Article 3 on *Mercury Supply Sources and Trade* and of Article 5 on *Manufacturing Processes in Which Mercury or Mercury Compounds Are Used*.[18] It should be noted that Articles 3 and 5 do not apply to mercury-added products and manufacturing processes that utilize mercury added products. Instead, they are primarily concerned with mixtures of mercury with other substances, including alloys of mercury, with a mercury concentration of at least 95 per cent by weight and mercury compounds including mercury (I) chloride (or calomel), mercury (II) oxide, mercury (II) sulphate, mercury (II) nitrate, cinnabar and mercury sulphide. Nevertheless, Parties are currently focused on establishing national inventory reporting processes that will likely be used over the coming decades to assist with the phase out of mercury use where possible. In addition, mercury inventory reporting processes are meant to fulfil Treaty obligations related to information exchange, awareness, and education as directed by Articles 17 and 18 previously discussed. The first reports were to be submitted by each of the 137 parties by 31 December 2021.

UN Environment

UN Environment plays a critical role in driving the elimination of anthropogenic mercury pollution. First, UN Environment hosts the Minamata Convention on Mercury. Second, it tabulates regional air emissions and water releases every five years (2010, 2015, 2020, etc.) and publishes the data in a detailed technical report approximately three years later (2013, 2018, 2023, etc.). The summary of the technical report is entitled *UN Environment Global Mercury Assessment* and is a complimentary download.[3] Reading the report is an insightful way to understand trends in global mercury inventories over time. Finally, UN Environment maintains an international database known as Comtrade which tracks and reports legal international exports and imports of elemental mercury. While UN Environment is not specifically legislating mercury restrictions, it is highly involved in shaping and implementing the global policy of Minamata, educating member nations and the world at large, and monitoring and reporting on both international mercury shipments and changes to global inventories.

21. Viability of UV LED Curing as an Alternative

Ultraviolet light emitting diodes (UV LEDs) emit energy without the use of mercury and represent the most promising mercury-free alternative to conventional UV curing systems. As a result, the regulatory community and users of UV curing technology are closely monitoring the evolution and adoption of UV LED technology. The broad range of existing UV curing applications, however, will continue to require a mix of conventional mercury vapor and LED lamps for the foreseeable future.

UV LED curing technology is a viable alternative for some processes currently using UV emitting mercury vapor lamps as well as conventional processes looking to embrace UV curing for the first time. The two main requirements are that 1) LED formulated chemistry be used instead of chemistry designed for broad-spectrum lamps and 2) energy emitted by the LED curing system must be matched to the needs of the chemistry and production process. A single LED system and formulation set that is universally suitable for every existing curing application across all market uses does not exist.

The requirements of the chemistry and the output of the LED system are two incredibly critical factors. While progress is being made and many applications have been commercialized, it has not yet been possible to re-formulate all SKUs of conventional UV chemistry for the narrow spectral band of LED curing systems. In addition, not all LED curing systems, even when specified at the same peak irradiance (W/cm^2) and wavelength (nm), emit the same total energy (J/cm^2). In general, a greater level of total emitted UV energy is necessary for more demanding formulations and faster line speeds while lower levels of emitted UV energy are often sufficient to crosslink more reactive chemistry and processes run at slower line speeds.

In cases where LED chemistry 1) does not yet exist, 2) is not possible to formulate, or 3) the LED system is not technically, economically, or practically suited to deliver enough energy for the chemistry or production process, mercury lamps remain the only UV curing option. For these applications, additional development and innovation are required to make UV LED curing feasible. Consequently, the answer to the question of whether UV LED technology is a viable alternative to mercury vapor lamps always depends on the specific needs of each application and production process, the LED system, and the chemistry.

Many variables affect curing processes and the viability of UV LED curing. They include the requirements of the chemistry, the specific output of the LED lamphead(s), the distance the LED lamphead(s) must be mounted from the cure surface, integration of the LED system and ancillary components into the machine or production line, the press or line speed, the dwell time, and the final performance requirements of the cured material(s). As a result, those interested in LED curing technology are highly encouraged to speak with their current formulation supplier, OEM machine builder, and UV system supplier to determine whether an LED retrofit to an existing machine or an LED installation on a new manufacturing line or press is feasible with current technology.

The good news is that the overriding market potential of UV LED curing, increasing engagement by potential users, and steady adoption by manufactures is more firmly established with each passing year. This is evidenced by the large number of conventional UV system suppliers, formulators, and OEM machine builders now offering and continuing to expand LED solutions. New companies are also entering the supply chain in hopes of capturing a share of existing and forecasted revenue streams, and novel processes are even being developed for LED curing that are simply not feasible with mercury vapor lamps. Another positive indicator is that UV LED curing continues to receive considerable attention at conferences and tradeshows and in journal articles and webinars. This is because LED suppliers are actively striving to reach growing numbers of manufacturers seriously considering the technology and in pursuit of the latest process and product information.

A positive global trend highlighted in the 2015 UN Environment inventory report shows general use of mercury in mercury-added products such as batteries, lamps, dental applications, and others is in steady decline.[2] Interestingly, this shift away from mercury began prior to the Minamata Convention which was adopted in 2013 and entered into force in 2017. As each industry develops technically and economically viable solutions, there is a natural progression away from mercury. This will ultimately prove to be the case for UV curing as well.

22. History of UV LED Technology

UV LEDs are high-tech electronics known as semiconductors. They are also the technological extension of visible and infrared LEDs. While longer wavelength visible and infrared LEDs have been commercially available since the late 1960s and 1970s, raw diodes capable of emitting UVA wavelengths slightly outside the visible spectrum did not exist until the late 1990s and did not trickle into the UV curing supply chain until the early 2000s. Decades of ongoing innovation throughout the entire semiconductor industry drove significant improvements across all relevant technical and commercial product specifications and made the evolution of UV LEDs possible.

Today, visible and infrared LEDs are incredibly economical and widely used as indicator lights and communication signals in remote control systems. Expansion into backlighting, general lighting, jumbotrons, UV curing, sterilization, disinfection, and purification among other uses is the direct result of technical breakthroughs for blue LEDs that occurred in the 1990s by Professors Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura. In 2014, these three individuals were honored with a Nobel Prize in Physics for their collaborative and revolutionary work in LED development.

Prototype UV curing lampheads made with LEDs first appeared between 2004 and 2006. The devices emitted minimal output, were incredibly inefficient, did not last long in operation, were considerably more expensive than existing mercury vapor lamps, were generally limited to narrow widths (10 to 25 mm) and short lengths (less than 150 mm), required mounting within 10 mm of the cure surface, and did not cure broadband formulated inks, coatings, and adhesives. While these early designs were innovative and promising, they were simply not a viable substitute for mercury vapor lamps.

Fortunately, UV LED technology has significantly improved over the last 18 years and is experiencing increasing market share in certain segments. The latest versions of the technology are more powerful, more economical, more efficient, and capable of being packaged into longer lamphead lengths and wider widths and, in some cases, can even deliver reasonable irradiance (W/cm^2) when mounted up to 150 mm or more from the cure surface. Additional development work in devices, optics, chemistry, and processes, however, is necessary to expand market adoption and establish feasibility across all UV curing applications and all UV curing formulations.

Between 2005 and 2010, UV LED curing garnered some commercial use with spot cure adhesives, UV digital inkjet wide-format sign printers, UV digital inkjet pinning, and UV digital inkjet marking and coding. Market adoption continues to grow in these areas but does not yet represent 100% of new system purchases. Between 2010 and 2020, UV LED curing expanded into analog printing segments including screen, flexo, and offset; fiber optic primary coating; wood fillers; and additional UV digital inkjet applications in narrow web label, product decoration, and corrugated; however, UV LED curing still represents a small, albeit rapidly growing, portion of the overall installation base in these markets.

Figure 18: Flexo narrow web label press (left) and sheetfed commercial offset press (right) equipped with UV LED curing technology.

With respect to industrial coatings that deliver more demanding performance properties, suppliers and end users have recently begun to explore the use of UV LED curing for non-printing applications such as hardcoats, clearcoats, topcoats, overcoats, silicone release, hotmelt adhesives, and other functional coatings. Significant challenges remain in developing these LED solutions, but suppliers are increasingly committing resources and continued progress is expected over the coming decade.

23. Impediments to Universal UV LED Adoption

As with any significant advancement in technology, there are impediments to universal widespread adoption. In the case of UV LED curing, impediments are attributed to unique requirements related to 1) chemistry, 2) UV LED semiconductors and curing systems, 3) material handling, 4) education, 5) economics, and 6) the need for existing users to requalify/recertify proven processes that presently use conventional curing technology. Overall, the pace of adoption and how it is constrained by these six factors has a lot to do with the great diversity of UV curing applications and the nature of their respective production installations.

UV curing processes involve a plethora of disposable and durable manufactured items, produce final products deployed across a long list of end uses with wide ranging performance requirements, and rely on different chemistry and application methods that must be developed specifically for LED technology. There is also a large globally installed base of mercury vapor lamps currently in operation with useful life remaining. Replacements, conversions, upgrades, and retrofits to existing lines most often occur, and are more easily justified, when mercury vapor systems approach end-of-life, when long running product models are discontinued, thereby, presenting an opportunity for a switch in curing system for new models, when a positive ROI is established, when clear process and performance improvements are demonstrated, and when corporate sustainability goals such as reducing energy consumption factor into curing system selection.

UV curing surfaces include webs, sheets, and 3D parts that are produced from a wide range of natural and synthetic materials. These surfaces can be flat, complex in shape, and even consist of populated assemblies. Widths span just a few millimeters all the way to 2.5 meters and beyond. Line speeds range from a few meters per minute to 1000 mpm or more. In other cases, cure surfaces are stationary during UV exposure and are positioned under a lower energy UV source for periods that span a few seconds to tens of seconds and longer. Complicating things further, UV curing is utilized across numerous industries with vastly different performance, dynamic material handling, integration, and certification requirements. Production environments include the cleanest of clean rooms as well as the dirtiest, non-climate-controlled plants located everywhere from sea level to mountain-high elevations.

The consequences are that an infinite number of process permutations span all the various UV formulations, formulation application methods, cure surface materials, final cure properties, process set-ups, and installation environments. As a result, each current use or application category potentially needs a slightly different and somewhat customized UV LED solution that must be developed, tested, proven, and implemented. Each solution requires all necessary components work together within the larger process while simultaneously delivering desired results.

For each application category, all aspects of conventional UV curing must be re-assessed and re-deployed for LED technology just as it was originally done for mercury lamp technology. Unfortunately, this can be a resource intensive exercise requiring financial outlays, time and staffing, close collaboration throughout the supply chain, and clear and reliable forecasts from potential users. As a result, UV curing companies, formulators, and machine builders offering LED technology tend to focus scarce resources on applications best suited to today's LED capabilities and markets more willing to embrace new technology. Consequently, projects requiring significantly greater innovation and investment, such as functional coatings, are often delayed in favor of those presenting more immediate returns such as printing inks. LED development activity is also not evenly spread across global geographies. Most is occurring in parts of North America, Europe, and East Asia with little to no activity in other regions of the world.

A notable impediment continues to be the fact that mercury vapor lamps and LEDs do not emit the same spectral output and, therefore, are not a direct swap without developing new chemistry and changing other process components and variables. Mercury vapor lamps are broadband emitting sources that radiate VUV, UVC, UVB, UVA, and UVV wavelengths between 100 and 450 nm as well as portions of the visible (400 to 700 nm) and infrared bandwidths (700 nm to 1 mm). By contrast, UV LED sources are quasi-monochromatic and commercially limited to narrow bands of UVA and UVV. The respective LED spectral outputs have center wavelengths at 365, 385, 395, and 405 nm. A visual comparison of irradiance verses wavelength for broad band mercury (green profile) and LED (purple profiles) is provided in Figure 19. The chart highlights the significant disparity in UV output that exists between technologies. In cases where this narrow range of output can be aligned to the reactive mechanisms in the chemistry, LED adoption moves forward. In cases where it cannot, use of mercury vapor lamps persist.

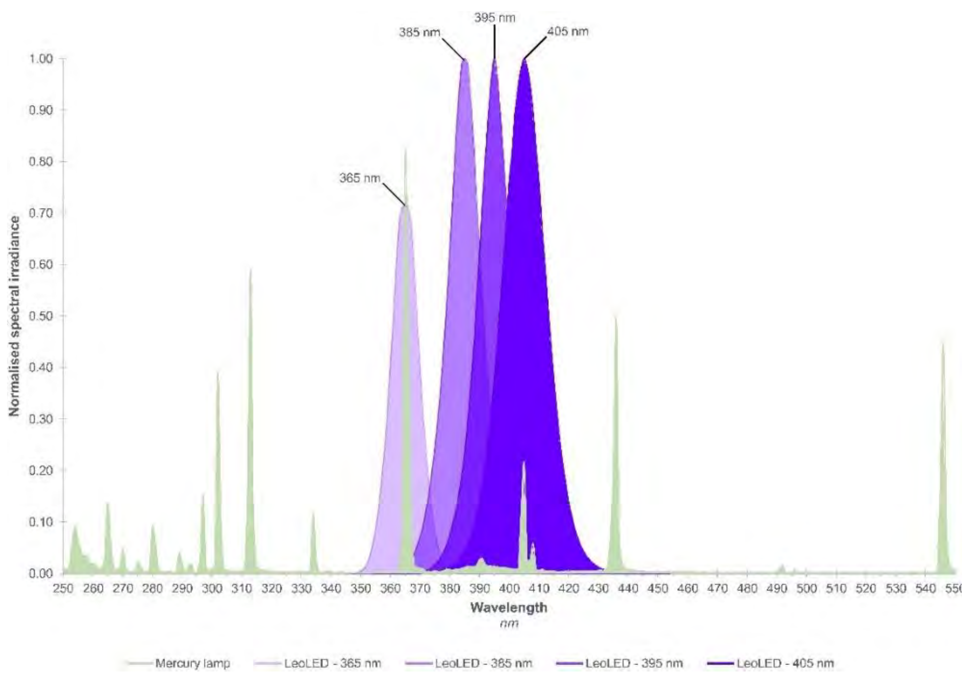

Figure 19: Mercury Vapor Spectral Output vs LED Spectral Output.

The continued need for mercury vapor lamps is most evident with industrial hardcoats and functional coatings such as silicone release, slip, anti-slip, anti-skid, and hotmelt adhesives. These formulations have always been designed to react to shorter UVC wavelengths around 254 nm to produce specific functional properties in cured products. 254 nm does not align with the output of commercial LED curing systems which are limited to longer UVA and UVV wavelengths. Unlike inks and adhesives, many functional chemistry formulations simply do not react to longer UVA and UVV wavelengths, and chemistry that is designed to react can discolor. For inks and graphic coatings, discoloration can be masked through pigments or innovatively blending reactive ingredients. The effectiveness of these tactics; however, is less viable with industrial hardcoats and clearcoats. These materials often require complete optical transparency, and changes to the chemistry currently produce inferior mechanical and chemical properties in the cured coating.

Fortunately, shorter wavelength UVC LEDs are actively being developed by semiconductor fabricators. These offerings currently exist as expensive prototype solutions that are not yet economically or technically viable for real-world manufacturing processes. Output from these UVC devices remains low and limited to a few non-ideal curing wavelengths between 275 and 285 nm. Source life and efficiencies are also currently poor. In general, the performance of UVC and UVB LEDs are approximately where UVA LEDs were ten years ago. In applications and processes where it is possible, chemistry should be formulated to react to UVA LEDs as these are the most efficient, most economical, and most readily available. In applications and processes where this is not possible, the industry may have to wait for UVC LEDs to evolve further or for new reactive molecules to be invented.

24. Achieving Widespread UV LED Adoption

The best way to achieve widespread UV LED curing adoption is through industry collaboration that works to deliver complete solutions with clearly demonstrated and measurable value. All aspects of the process should be engineered as a proven solution and not supplied as discrete, disparately engineered components, material handling, and chemistry.

While the present and future of UV curing most certainly includes UV LED technology, the emitting source is only one part of the total solution. Other necessary parts include availability of suitable chemistry; the ability to integrate the lamphead and system design into existing machines and incorporate ancillary technologies such as chilled rollers, chilled plates, and nitrogen inertion; and an attractive economic scenario for companies wanting to use the technology in manufacturing processes. Initial capital expenditures, operating costs, and scrapping existing and viable mercury lamp installations with remaining life all factor into the economic justification.

While UV LED curing progress is being made in all areas, feasibility varies widely by market segment and application. For markets where UV LED curing is not currently used, remaining challenges typically lie in reformulating more demanding chemistry, potentially creating new molecules, developing UV LED emitting systems with shorter UVB and UVC wavelengths to cure chemistry that does not react to UVA, designing efficient and economical LED lampheads that can cure at desired production speeds and/or when mounted further from the cure surface, and the time and resources necessary to demonstrate capabilities and optimize processes on existing manufacturing lines.

All aspects of UV LED curing technology are improving and trending in the right direction, and significant ongoing adoption by OEMs and end users is anticipated in the coming years. A complete universal shift to UV LED curing across all markets and applications, however, is not possible today and requires further collaboration throughout the supply chain for at least another 10 to 20 years. Suppliers need to identify and/or develop suitably matched UV LED curing systems and formulations for all existing applications as well as new ones. Once viable lamps and chemistry are commercially available, it can take up to a decade or more for new technology to penetrate the intended market segment. It simply takes time for users to self-educate, gain confidence in the technology, begin replacing ageing systems, direct new lines to UV LED, and requalify jobs and processes particularly those in the food packaging, medical, and automotive industries. Fortunately, the entire UV curing industry is increasingly investing in LED technology and its further development, much of which is being driven by corporate sustainability targets and the energy savings achieved by transitioning to LED curing. Users are also naturally gravitating toward UV LED curing when it is proven suitable for their respective application and industry. Interestingly, this transition is occurring organically and without regulation.

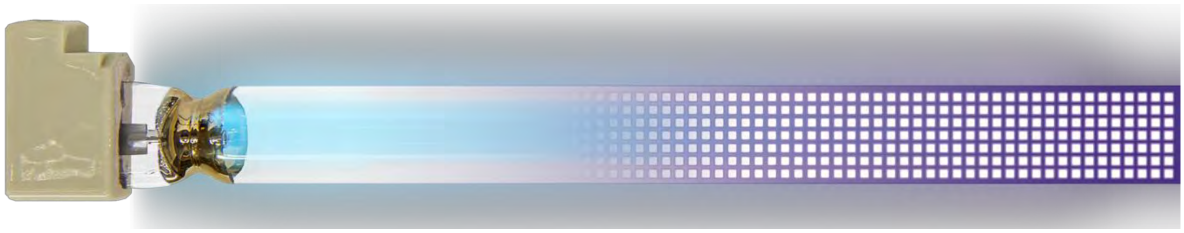

Figure 20: The transition from mercury vapor to UV LED is on its way!

Another consideration worth noting is that as the general lighting industry increasingly shifts to LED technology, manufactures of consumer and commercial lighting products will ultimately exit the conventional lamp market altogether. The potential impact is that the supply chain furnishing lamp components used in the manufacture of UV lamp assemblies may become constricted should this trend in general lighting accelerate. While this is not yet occurring en mass, shifts in the supply chain over the next 10 to 20 years have the potential to increase the cost of UV lamp manufacturing by decreasing the availability and quality of components used in lamp construction. Hopefully, shifts in the supply chain will be balanced against users of UV curing voluntarily embracing UV LED technology as an alternative to medium-pressure mercury vapor lamps. This will allow lamp and OEM suppliers to direct available supplies of UV curing lamps toward curing markets in need of more development time before a total shift to UV LED technology is viable.

25. Transitional Approach to UV LED Curing

UV LED curing technology is an increasingly solid option for many applications such as flexo, offset lithography, screen, and UV digital inkjet among others. UV curing system suppliers are embracing the market shift to UV LED curing and working closely with clients to determine whether a mercury or UV LED solution is best for each set of circumstances. While the shift to LED is well underway, the full transition will likely span some portion of the next decade or more with the specific length of time dependent on unique requirements for each industry and application.

In an effort to enable users to transition at a pace that meets their comfort tolerance, hybrid ArcLED curing systems have been developed with interchangeable mercury and LED quick change cassettes. These hybrid lampheads are driven by common control systems and rectifying power supply units (PSUs) that supply AC power to the mercury vapor lamps and DC power to the LEDs. Hybrid designs enable manufacturers to utilize arc lamps and LED curing technology simultaneously and interchangeably across jobs. This technology, shown in Figure 21 (left), bridges the gap until LED chemistry and LED curing systems are viable across all a user’s applications and markets. For applications that do not require hybrid capability, a dedicated LED lamphead, displayed in Figure 21 (right), is another option with lampheads in both styles available in continuous lengths up to 1.7 meters. With respect to formulations, many suppliers now offer dual-cure formulations that are specifically designed to react when exposed to longer wavelength LEDs with the recipe further adjusted so that it also cures when exposed to broadband mercury lamps.

Figure 21: Hybrid cassette style UV curing system (left) and dedicated compact UV curing system (right).

With respect to collaboration with industry co-suppliers, UV curing system suppliers should be diligently working with formulators to expand commercial offerings of UV LED curable inks, coatings, and adhesives. They should also actively engage with formulators on novel UV LED chemistry that leverages LED's unique benefits. System suppliers should work closely with original equipment manufacturers (OEMs) to determine when and where UV LED curing technology can be successfully utilized. System suppliers should strategically engage with partner OEMs to develop UV LED curing systems that can be easily integrated into current as well as legacy and future machines as this eases adoption and reduces integration costs. Finally, it is necessary to educate the market on mercury vapor and UV LED curing technology, participate in industry initiatives that educate users and promote use of the technology, and assist users in navigating their own personal transition to UV LED curing.

26. Conclusion

There are currently no new restrictions in any country worldwide that specifically ban mercury UV curing lamps from production, use, export, import, or general shipment, and no new restrictions specifically addressing mercury vapor UV curing lamps are anticipated in the immediate term. Global regulatory policies driven by REACH, RoHS, TSCA/Lautenberg Act, and the Minamata Convention on Mercury as well as regulatory bodies such as the European Commission, the U.S. Environmental Protection Agency, and UN Environment are meant to reduce or eliminate anthropogenic mercury use. While complete mercury elimination is not possible today, restrictions and enforcement are expected to become stricter over time. The specifics of adopted policies, the means through which enforcement is pursued, and corresponding phaseout timelines, however, can sometimes be difficult to interpret and implement. As a result, legislation and policy crafted by REACH and RoHS in the EU, by the UK Parliament, and by the EPA in the U.S. along with legislation in other countries should be carefully and regularly reviewed with steps taken to best ensure compliance with local laws.

This author does not believe a global ban on the use of mercury vapor lamps will produce an immediate and complete shift to UV LED technology. It simply is not technically, economically, or practically possible due to the wide range of UV curing applications and processes that have not yet been suitably developed for LED and the large installation base that must be converted. An all-inclusive ban disproportionately favors economically advantaged countries at the expense of third world users. Furthermore, a ban on mercury vapor UV curing lamps will not make a significant impact in reducing global anthropogenic mercury use and environmental pollution due to the safe practices of the industry, the low level of mercury content within the lamps, the reclamation process available through recycling, and the rapidly growing demand and use of mercury by Artisanal Small-Scale Gold Mines (ASGMs) in Asia, Africa, and South America and vinyl chloride monomer (VCM) producers in China.

Premature total use bans on UV curing lamps primarily serve to destroy the value of existing UV curing assets, inhibit production capabilities of manufacturers, and drive-up product prices when manufacturers have no other option than to embrace less desirable alternative technologies. This includes various curing and drying technologies that are less efficient, do not deliver comparable end use product performance requirements, consume higher levels of energy, result in inferior and/or more expensive end-use products, and lead to other negative consequences on the environment such as the emission of greenhouse gases and greater carbon footprints.

On the bright side, the global community should be highly encouraged by the potential of UV LED curing technology to facilitate the continued reduction and eventual elimination of mercury-added products. In fact, UV LED curing is well positioned to steadily capture a significant portion of UV curing applications over the next one to two decades. As confidence builds and technology and application feasibility improve, more users and markets will make the switch, which is ultimately the goal of global regulators. This will occur regardless of regulatory involvement since UV LED curing has the potential to be the preferred emitting source for all curing applications. In the meantime, users of UV curing are encouraged to educate themselves on the technology, actively engage in the development process, and recycle all mercury vapor lamps at the end of useful life.

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