ASSESSING THE RISK OF MERCURY FROM ON-LINE UV LAMP BREAKS

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ABSTRACT

This paper focuses on examining the risks associated with on-line lamp breaks in ultraviolet light (UV) drinking water treatment facilities. UV lamps generate UV light through the vaporization of elemental mercury, by using energy through temperature and pressure to drive the mercury into a vapor phase. Mercury is a heavy metal and is regulated in drinking water by the United States Environmental Protection Agency (USEPA) through the Safe Drinking Water Act (SDWA). If an on-line lamp break did occur, and mercury was released, techniques such as dilution or treatments must be employed to insure that the resulting concentrations in the drinking water are maintained lower than that of the Maximum Contaminant Level (MCL) which is 0.002 mg/L as set by the USEPA. Research conducted by the USEPA and others, reveals many unique properties that the element mercury demonstrates. This research also aided in pinpointing the potential risks to both water consumers and UV treatment facility operators. In many cases, the risk of inhalation of vapor phase mercury by treatment plant personnel responsible for accessing the mercury released and conducting clean up activities is the most significant concern that needs to be addressed. For many water systems the dilution achieved by the flow rates being treated or by the downstream volume provided by the clearwell or distribution system piping will insure that the mercury concentration reaching the public is well below the MCL and often reaches non-detectable levels. In smaller systems, where adequate dilution may not occur, other operational controls and treatments may be necessary to insure the risk of ingestion of mercury from the contaminated water is alleviated.

INTRODUCTION

UV treatment of water is more effective than standard chlorination, and while historically the U.S. has been slow to implement UV into current drinking water systems, many areas of Europe and Canada have successfully updated water systems to include UV treatment (Malley and Burris, 2001). As the number of systems updating to UV increases in the U.S. and throughout the world, it is important to note that potential risk factors can emerge with the increased use of mercury vapor lamps (UV lamps) in drinking water treatment systems. Mercury lamps function by volatilizing elemental mercury into a vapor phase, which allow the lamps to ionize the mercury, and as an effect, produce UV light. In this process, there is a potential for lamp breaks to occur, in which mercury can be released and enter the distribution system. After mercury enters the system, it has the potential to directly affect the unsuspecting water consumer. It is unclear how mercury will react when it enters a drinking water distribution system and additional research on this question is needed.

This paper is focused on *on-line lamp breaks* because they have the potential to pose health risks to water consumers. On-line lamp breaks pose the most risk because they occur when water is flowing over the lamps, and this treated water is released to the downstream processes or clearwell. Actual calculated health risks directly associated with on-line UV lamp breaks in drinking water treatment systems are unknown at this time but their potential has been estimated in several studies to be small.

THE UV REACTOR

Figure 1 depicts the setup of a typical UV reactor in a drinking water treatment plant. It is important to note that UV lamps in a reactor may be oriented differently depending on the specific design application. In larger drinking water facilities, UV lamps are commonly oriented perpendicular to the direction of the water flow through the system. A UV reactor works by passing water around the mercury vapor lamps that generate UV. "The lamps are situated across the reactor, so the water will receive adequate exposure to the UV lamps in order to attain optimum treatability" (USEPA 2006).

In the reactor represented in Figure 1, water schematically flows through the influent pipe. After traveling the length of the pipe, the water enters the UV reactor where the UV lamps are contained. The UV lamps are housed in a *quartz sleeve* that functions to protect the lamp. The UV reactors often contain a wiper mechanism that wipes the sleeve if a film (due the suspended particles or precipitated ions in the water) develops, which could interfere with the intensity of the UV light.

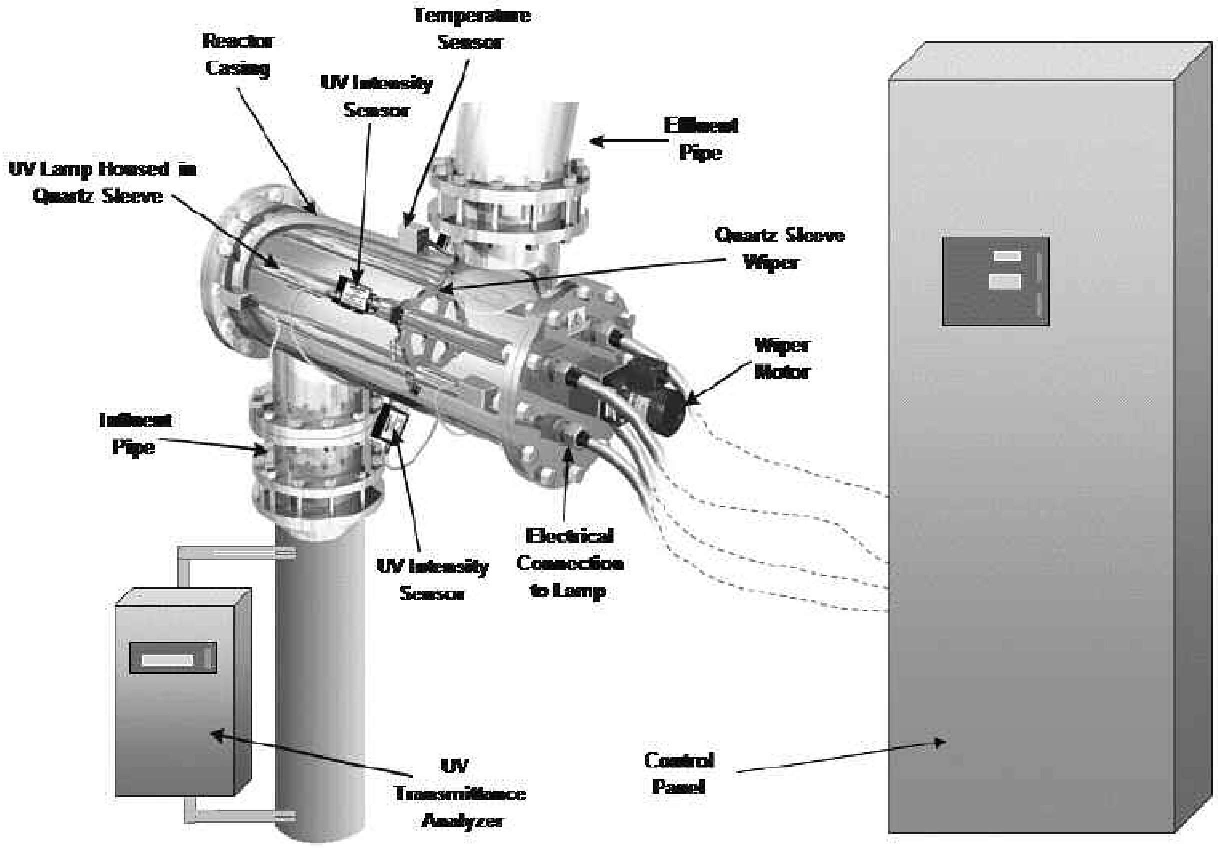

Figure 1: *Typical UV Reactor in a Drinking Water Treatment System (courtesy of and adapted from Severn Trent Services). Note not to scale.*

UV LAMP BREAKS

Some lamp breaks have occurred in distribution systems. Risks can surface if UV lamps break because a typical medium pressure mercury vapor lamp contains approximately 400 mg of elemental mercury (Malley 2006). If a break occurs, elemental mercury may be present, in vapor or colloidal form, in the downstream piping. For ease, lamp breaks have been divided into two categories (USEPA 2006):

Off-line Lamp Breaks

The first type of lamp break that can occur is known as an off-line lamp break. These breaks can occur during transportation and setup or routine offline maintenance, and is defined as a break that occurs when water from the system is not flowing through the UV reactor. There is no risk associated with the water consumer in this type of break. When the lamp is not in use, the mercury can be found in a liquid phase, which is less hazardous than when it is found in vapor phase. The only risk associated with this type of break is to the transporters or workers. If individuals are properly trained, and the lamps are handled correctly, then a break of this type can be avoided and risks of exposure minimized (USEPA 2006).

On-line Lamp Breaks

An on-line lamp break occurs when the quartz sleeve and the UV lamp breaks while water is flowing through the UV reactor. When proper training and precautions are followed, this type of break is rare. An on-line lamp break has the potential to directly impact the water consumer. There is greater risk associated with this type of lamp break than an off-line lamp break because it occurs while water is flowing through the UV reactor. When this type of break occurs, the elemental mercury is in a vapor state, due to the high temperatures that the lamp reaches during UV generation (USEPA 2006).

CASE STUDIES

Several case studies have revealed that lamp breaks in operating facilities are rare, but they can occur due to factors listed below:

1. *Lamp manufacture and handling:* New lamps can fail due to manufacturing problems. Mishandled lamps can also fail upon installation. This is often considered an off-line lamp break (USEPA 2006).
2. *Power compatibility:* Power surges and electrical component failure can cause lamp damage and failure.

Overdriving lamps with excessive power input can cause lamp failure. This is most often considered an on-line lamp break (USEPA 2006).

3. *Orientation:* UV lamps within a UV reactor can increase the potential for on-line lamp breaks. It is essential to keep in mind that orienting lamps perpendicular to the ground can result in differential heating of the lamp and the sleeve, which can lead to cracking of the lamp and sleeve while the lamp is in use in the reactor.
4. *Faulty manufacturer design:* This was the leading cause of most of the mercury release incidents. The first case occurred because the applied power exceeded the tolerances of the lamp, causing the lamp to burst from within. The second case occurred due to the vertical orientation of lamps in the reactor that resulted in differential heating, and eventual cracking of the lamp and lamps sleeve because the heat accumulated at the tops of the lamp and sleeve. A third case occurred due to high operating temperatures, which resulted in deformation of the lamp sleeve. The lamp sleeve sagged and on contact with the lamp, both the lamp and the lamp sleeve broke. Another case occurred because of a manufacturing defect in which the lamps exploded after approximately 300 hours of operation. The last break occurred after the lamp manufacturer used contaminated quartz material (USEPA 2006).
5. *Damage from debris:* Impact from debris was the second most common cause of lamp breaks involving mercury release. There are currently five documented cases involving debris damage. The first case involved stones that entered the reactors and struck the lamps. The second case occurred because gravel entered the reactor through the booster pump and struck the lamp (USEPA 2006).
6. *Loss of water flow and temperature:* This was a cause of two documented breaks. In one case, the lamps were left on and allowed to reach high temperatures (600°C) in empty non-operating reactors. Restoration of flow caused cooler water (20°C) to break the lamps. This occurs due to exposure to extremely hot conditions, immediately followed by cold conditions, or vice versa (USEPA 2006).
7. *Operator error:* There was one documented case of an operator error when a forklift collided with the on-line reactor that resulted in a lamp break and release of mercury (USEPA 2006).
8. *Water Hammer:* Several UV manufacturer's have reported that rapid changes in pressure gradients often resulting from rapid opening or closing of valves can result in extreme lamp, sleeve and wiper system vibrations that can crack sleeves or damage seals allowing water to enter the UV lamps and ultimately cause lamp breakage.

ABSORPTION OF MERCURY

Based on thorough research conducted under the USEPA and other professionals, it has been determined that the absorption of elemental mercury vapor occurs rapidly through the lungs, but is poorly absorbed from the gastrointestinal tract. Studies in human volunteers have shown that approximately 75–85% of an inhaled dose of elemental mercury vapor was absorbed by the body (USEPA 1997).

Research on rats conducted by Bornmann et al. (1970) further validates that liquid metallic mercury is poorly absorbed from the gastrointestinal tract. In rats, less than 0.01% of an ingested dose of metallic mercury was absorbed (USEPA 1997). The release of mercury vapor from liquid elemental mercury in the gastrointestinal tract is limited. Research conducted by Berlin (1986) suggests that within the gastrointestinal track the elemental mercury undergoes rapid reactions and a mercuric sulfide coating forms around the ingested mercury. This coating acts to prevent adsorption of the elemental mercury and minimizes volatilization of the mercury within the body (USEPA 1997).

Absorption of elemental mercury through dermal contact is also poor. The rate of dermal absorption is sufficient to account for less than 3% of the total amount absorbed during exposure to mercury vapor (greater than 97% of the absorption occurs through the lungs) (USEPA 1997).

The water consumer is at a much lower risk for mercury poisoning than UV technicians if a break occurs. Given the typical partial pressures (0.1–10 atm) and operating temperatures of UV lamps (100–900°C), virtually all of the elemental mercury in the lamp will be in the vapor phase when the lamp is on-line and in use (USEPA 2006). In mercury amalgam lamps, the alloy will dictate the total amount of vapor phase mercury in the lamp during operation and this amount will be lower than in non-amalgam lamps, but the quantities of mercury in the vapor will still result in an inhalation health risk. As the mercury vapor cools to typical water conditions of 20°C or less and 1 atm, the mercury will return to its liquid state. Thus, responders to a lamp break must be trained to deal with mercury that is initially in a vapor phase, and later in a colloidal phase downstream of the break. Anecdotal information suggests that vapor phase mercury concentrations in a shutdown and drained UV reactor can remain high (above OSHA standards) for several hours after a break has occurred.

ELEMENTAL MERCURY

It is important to note that the solubility of mercury in water is relatively low, only about 62 µg/L under standard temperatures and pressures (Malley 2006), which means that the majority of the mercury will likely precipitate out of solution instead of dissolving in the water once equilibrium is achieved. Further, mercury has a density of 13.59 g/mL at 25°C, suggesting that droplets of elemental mercury will have a high terminal settling velocity. However, despite the large density, Mercury is unique because it has the ability to evaporate when released into water or soil (Berlin 1986).

CALCULATING THE RFD AND MCL FOR MERCURY

The USEPA established the oral Reference Dose (RfD) based on the assumption that thresholds exist for certain toxic effects in human beings due to mercury exposure such as cellular necrosis. It is expressed in units of mg/kg-day. "The RfD is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime" (USEPA 1995).

Dose conversions in the three studies employed a 0.739 factor for $HgCl_2$ to Hg^{2+}, a 100% factor for subcutaneous (s.c.) to oral route of exposure, and a time-weighted average for days/week of dosing. This RfD is based on the back calculations from a Drinking Water Equivalent Level (DWEL), recommended to and subsequently adopted by the Agency, of 0.010 mg/L (USEPA 1995)

The U.S. EPA assumes the following standards when calculating the RfD for mercury:

- ∑ DWEL = 0.010 mg/L of mercury
- ∑ Average amount of water consumed = 2L/day
- ∑ Average bodyweight of adult = 70 kg

"The RfD of 0.0003 mg/kg/day is based on immune mediated kidney damage in three studies conducted in a sensitive strain of rats (Norway rats)" (USEPA 2002). Under the Safe Drinking Water Act (SDWA), the USEPA established a primary Maximum Contaminant Level (MCL) of mercury to be 0.002 mg/L (USEPA 1997). MCLs are enforceable and take into account the cost of removal of the pollutant from the drinking water source. The MCL is an enforceable standard, and all public water systems in the United States must meet this goal.

Therefore:

$$\text{RfD} = \frac{0.010 \text{ mg/L} \times 2 \text{ L/day}}{70 \text{ kg body weight}} = 0.000285 \text{ or } \sim\mathbf{0.0003\ mg/kg/day}$$

MASS BALANCE

A mass-balance analysis for several hypothetical online lamp failures in several different drinking water plants (Malley 2006) revealed that many systems with clearwells have the ability to dilute the potential concentrations of mercury released from the broken lamps to levels much lower than the USEPA's MCL of 0.002 mg/L. For example, if the clearwell has a volume of at least of 58,000 gallons, and the system is treating a minimum water flow of 3.3 Million Gallons per Day (MGD) the resulting concentration of mercury leaving the clearwell in a typical single, 400 mg-Hg lamp break scenario would be approximately 0.001 µg/L.

Small groundwater systems with close first users and systems devoid of clearwells are faced with a tougher challenge. This challenge can be mitigated in some cases by selecting UV lamps with a lower mercury content and or an amalgam mercury lamp which would mean that the amount of mercury released during a single lamp break would be reduced by as much as 75%. Another option for the smaller systems may also be to specify a UV reactor design where the mercury containing lamps do not come into direct contact with the water treated since there are a few reactors of this type being marketed for small systems. The operators of conventional UV reactors for small systems must adopt a standard operating plan in response to an online lamp break in which the water contaminated by the broken lamps must either be bypassed, or perhaps design adequate inline storage and dilution in order to ensure concentration reduction so the potentially contaminated water doesn't reach the consumer. Methods for treatment and removal of the released mercury are reviewed next.

TREATING MERCURY

USEPA has identified Best Available Technologies (BAT) for proper remediation of mercury-contaminated water in drinking water and wastewater systems. One example of a remediation system involves coagulation and filtration of mercury. Another way to treat the mercury, especially if it is in a large quantity, is through the use of granular activated carbon adsorption. In addition, lime softening with resulting precipitation and filtration, and reverse osmosis membranes are generally used to treat small quantities of mercury contamination in water (USEPA 2007).

Another treatment option in small systems is one that forces the mercury to cool and settle out using gravity, before it exits the UV reactor piping and enters the clearwell or distribution system. The theoretical conditions to insure adequate settling of the mercury can be estimated using simple Stoke's Law with turbulent flow modification calculations. These calculations suggest that over 99% of the debris and elemental mercury will be collected in a relatively simple drop-leg type stilling pipe. Mutti et al. (2005) showed, for smaller UV systems treating drinking water wells in Ontario, Canada, that a drop-leg type structure was designed into the downstream piping to provide a trap for the debris and mercury that may result from an online lamp break. This design is theoretically sound and should provide a trap for the majority of the debris and mercury released. However, no data on actual performance of these drop leg traps during an online mercury lamp break has been reported in the literature.

CONCLUSIONS

A typical medium pressure mercury vapor lamp will contain 400 mg of elemental mercury or less; larger systems and systems with clearwells need only be concerned minimally with on-line lamp breaks. This is because the vast amount of water flowing through the system will dilute the mercury concentration to a figure far below the MCL for mercury, as set by the USEPA. Even if all of the lamps were to break in a *typical* drinking water system, the water will be safely diluted. Systems lacking clearwells may have difficulties if an on-line lamp break occurs. Though documented breaks are rare, these can be serious, and need to be addressed properly so the operators know what to do if such a scenario arises. In many cases, the risk of inhalation of vapor phase mercury by treatment plant personnel responsible for accessing the mercury released and conducting clean up activities is the most significant concern that needs to be addressed. Operators should also be trained to properly treat and remove the mercury from the system, or be able to contain it safely until qualified personnel can arrive. By looking at the available data and studies conducted for mercury, the vapor is easily absorbed through the lungs, secondly, through the dermal layer, and poorly through the gastrointestinal tract. Therefore, the greatest risk from a lamp break is through inhalation of mercury vapor by the operators and technicians responsible for the clean-up in the drinking water treatment facility, and not to the consumers.

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