



New England Water Treatment Technology Assistance Center

University of New Hampshire • Durham, New Hampshire

PROJECT SUMMARY REPORT

Assessing the Risk of Mercury in Drinking Water after UV Lamp Breaks

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Problem statement/objective

Ultraviolet (UV) lamps generate ultraviolet 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 EPA 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) as set by the U.S. EPA. Research conducted by the U.S. EPA and others, reveals many unique properties that elemental 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 to 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 flowrates 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 of 0.002 mg/L 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. This paper focuses on examining the risks associated with on-line lamp breaks in UV drinking water treatment facilities.

Methodology

UV treatment of water is more effective than standard chlorination, and while historically the U.S. has been skeptical to implement UV into drinking water systems, many areas of Europe and Canada have successfully updated water systems to include UV treatment. 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 case mercury can be released and enter the distribution system. After mercury enters the system, it has the potential to impact the water consumer. It is unclear how mercury will react when it enters a drinking water distribution system and additional research on these questions is needed.

This report 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

The diagram (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 are oriented differently depending on whether they are treating drinking water or wastewater. In a drinking water system, UV lamps are oriented perpendicular to the direction of the water flow through the system. A UV reactor works by passing water through the mercury vapor lamps that generate UV. “The lamps are situated horizontally across the reactor, so the water will travel the length of the tubes of the UV lamps in order to attain maximum treatability” (U.S. EPA, 2006).

In the reactor represented in Figure 1, water enters through the influent pipe and enters the UV reactor where the UV lamps are contained, and may be oriented parallel or perpendicular to the direction of water flow. The UV lamps are housed in “quartz sleeves” that function to protect and thermally insulate the lamp. Often MP UV reactors contain a wiper system that wipes the sleeve when a film develops, that could interfere with the intensity of the UV.

UV LAMP BREAKS

Some lamp breaks have occurred in distribution systems. Risks can surface if UV lamps break, because each 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 UV reactor and immediately downstream of the reactor. For ease, lamp breaks have been defined and categorized into two categories (U.S. EPA, 2006):

1. 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, and is defined as a break that occurs when water from the system is not flowing through the lamp. 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 the 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 (U.S. EPA, 2006).

2. On-line Lamp Breaks:

An on-line lamp break occurs when the quartz sleeve that protects the UV bulb breaks. 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 lamp. 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 (U.S. EPA, 2006).

Results

CASE STUDIES

Several 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 considered an off-line lamp break (U.S. EPA, 2006).
- 2. Power compatibility:* Power surges and electrical component failure can cause lamp damage. Overdriving lamps with excessive power input can also cause lamp failure (U.S. EPA, 2006).
- 3. Orientation:* UV lamp orientation within a UV reactor can increase the potential for on-line lamp breaks. Orienting MP lamps perpendicular to the ground should be avoided since this 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 or design* 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 (U.S. EPA, 2006).
- 5. Damage from debris* impact 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 (U.S. EPA, 2006).
- 6. Loss of water flow and temperature* was a cause of two documented breaks. In one case, the lamps were left on and allowed to reach high temperatures (600 degrees Celsius), in empty non-operating reactors. Restoration of flow caused cooler water (20 degrees Celsius) to break the lamps. This occurs due to extreme thermal stresses on the UV lamps and sleeves from the rapid change in temperature (U.S. EPA, 2006).
- 7. Operator error:* There was one documented case of operator error when a forklift collided with the on-line reactor that resulted in a lamp break, and release of mercury (U.S. EPA, 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 and sleeve vibrations that can crack sleeves or damage seals allowing water to enter the lamps and ultimately lamp breakage.

ABSORPTION OF MERCURY

Based on thorough research conducted by the U.S. EPA and other professionals, it has been determined that the absorption of elemental mercury vapor occurs rapidly through the lungs, but is poorly absorbed

by 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 (U.S. EPA, 1997).

Research on rats conducted by Bornmann et al. (1970) further validated 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 (U.S. EPA, 1997). The study also showed that the release of mercury vapor from liquid elemental mercury in the gastrointestinal tract was very limited. Research conducted by Berlin (1986), suggests that within the gastrointestinal track the ingested elemental mercury undergoes rapid reactions and a mercuric sulfide coating form around the ingested mercury. This coating acts to prevent absorption of elemental mercury and minimizes volatilization (U.S. EPA, 1997).

Absorption of elemental mercury through dermal contact is very poor. The rate of dermal absorption accounts for less than 3% of the total amount absorbed during exposure to mercury vapor. Conversely, greater than 97% of mercury vapor absorbed was found to occur through the lungs (U.S. EPA, 1997).

Since mercury absorption is primarily through inhalation, following a UV lamp break the water consumer is at a much lower risk from mercury exposure than UV reactor technicians if a break occurs. Given the typical partial pressures (1-10atm) and operating temperatures of UV lamps (100-900 degrees Celsius), virtually all of the elemental mercury in the lamp will be in vapor phase when the lamp is on-line and in use (U.S. EPA, 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 degrees Celsius and 1 atm, the mercury will return to its solid 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 the break has occurred.

ELEMENTAL MERCURY

It is important to note that the solubility of mercury in water is relatively low, about 62 µg/L under standard temperatures and pressures (Malley, 2006), which suggests 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 degrees Celsius suggesting that droplets of elemental mercury once formed will have a high terminal settling velocity. However, despite the large density, elemental mercury is unique in its ability to evaporate when released to water or soil (Berlin, 1986).

CALCULATING THE RFD and MCL FOR MERCURY

The U.S. EPA 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” (U.S. EPA, 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 back calculations from a Drinking Water Equivalent Level (DWEL), which were recommended to and subsequently adopted by the EPA, of 0.010 mg/L: (RfD = 0.010 mg/L x 2 L/day/70 kg bw = 0.0003 mg/kg/day). (U.S. EPA, 1995)

The U.S. EPA assumed 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

Therefore:

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

“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)” (U.S. EPA, 2002). Under the Safe Drinking Water Act (SDWA), the U.S. EPA established a primary Maximum Contaminant Level (MCL) of mercury to be 0.002 mg/L or 2 $\mu\text{g/L}$ (U.S. EPA, 1997). MCLs are enforceable and take into account the cost of removal of the pollutant from the drinking water source. All public water systems in the United States must meet this MCL.

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 U.S. EPA’s MCL of 2 $\mu\text{g/L}$. For example, if the clearwell has a volume of at least 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 would be approximately 0.001 $\mu\text{g/L}$.

Small groundwater systems with close first users and systems devoid of clearwells are faced with a tougher challenge. The operators of such 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. Another option for the smaller systems may also be to specify a UV reactor where the mercury containing lamps do not come in contact with the water being treated since there are a few reactors of this type available to the small UV systems. Methods for treatment and removal of the released mercury are reviewed next.

TREATING MERCURY

U.S. EPA 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 (U.S. EPA, 2007).

Another possible design could be 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 necessary 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. Muti 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.

Recommendations

A typical medium pressure mercury vapor lamp will contain 400mg 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 amount of water flowing through the system and/or the clearwell volume will dilute the mercury concentration to concentrations that are far below the MCL for mercury, as set by the EPA. Mass balance analysis suggests even if all of the lamps in a typical MP UV reactor were to break in most *typical* drinking water systems, the water will be safely diluted by the time it exits the clearwell. Systems with low flows and or systems lacking clearwells may have difficulties if an on-line lamp break occurs. Though documented breaks are rare, these can occur, and need to be addressed properly so the operators know what to do if such a scenario arises. Operators should also be trained to properly treat and remove the mercury from the system, or be able to safely contain it 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. The greatest risk of exposure if an online mercury lamp break occurs is to the operators and technicians responsible for the clean-up in the drinking water treatment facility, and not to the consumers.

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Figure 1. Typical UV Reactor in a Drinking Water Treatment System

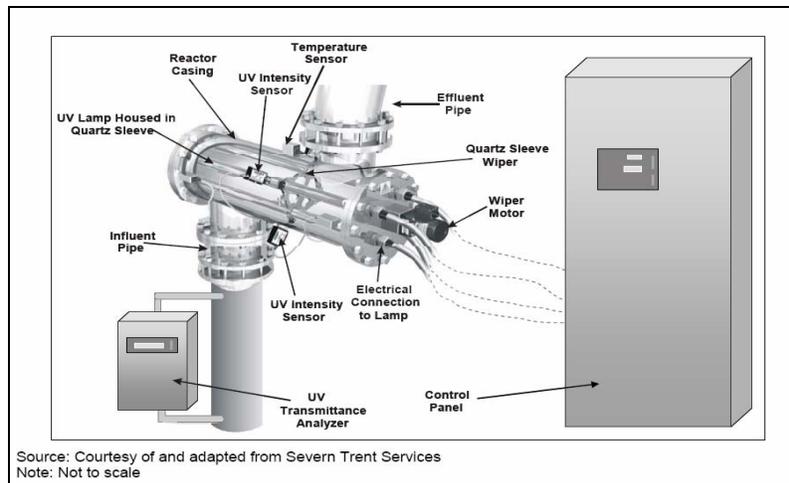


Figure 2: On-line UV lamp break

