Health Consultation

MERCURY AT A LIGHTHOUSE

SPLIT ROCK LIGHTHOUSE

TWO HARBORS, LAKE COUNTY, MINNESOTA

Prepared by the
Minnesota Department of Health Environmental Health Division

DECEMBER 18, 2009

Prepared under a Cooperative Agreement with the
U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Agency for Toxic Substances and Disease Registry
Division of Health Assessment and Consultation
Atlanta, Georgia 30333

Health Consultation: A Note of Explanation

A health consultation is a verbal or written response from ATSDR or ATSDR's Cooperative Agreement Partners to a specific request for information about health risks related to a specific site, a chemical release, or the presence of hazardous material. In order to prevent or mitigate exposures, a consultation may lead to specific actions, such as restricting use of or replacing water supplies; intensifying environmental sampling; restricting site access; or removing the contaminated material.

In addition, consultations may recommend additional public health actions, such as conducting health surveillance activities to evaluate exposure or trends in adverse health outcomes; conducting biological indicators of exposure studies to assess exposure; and providing health education for health care providers and community members. This concludes the health consultation process for this site, unless additional information is obtained by ATSDR or ATSDR's Cooperative Agreement Partner which, in the Agency's opinion, indicates a need to revise or append the conclusions previously issued.

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FOREWORD

This document summarizes public health concerns related to a historical site in Minnesota. It is based on a formal site evaluation prepared by the Minnesota Department of Health (MDH). For a formal site evaluation, a number of steps are necessary:

- *Evaluating exposure:* MDH scientists begin by reviewing available information about environmental conditions at the site. The first task is to find out how much hazardous chemical is present, where it is found on the site, and how people might be exposed to it. Usually, MDH does not collect its own environmental sampling data. Rather, MDH relies on information provided by the Minnesota Pollution Control Agency (MPCA), the US Environmental Protection Agency (EPA), and other government agencies, private businesses, and the general public.
- *Evaluating health effects:* If there is evidence that people are being exposed—or could be exposed—to hazardous substances, MDH scientists will take steps to determine whether that exposure could be harmful to human health. MDH's report focuses on public health— that is, the health impact on the community as a whole. The report is based on existing scientific information.
- *Developing recommendations:* In the evaluation report, MDH outlines its conclusions regarding any potential health threat posed by a site and offers recommendations for reducing or eliminating human exposure to pollutants. The role of MDH is primarily advisory. For that reason, the evaluation report will typically recommend actions to be taken by other agencies—including EPA and MPCA. If, however, an immediate health threat exists, MDH will issue a public health advisory to warn people of the danger and will work to resolve the problem.
- *Soliciting community input*: The evaluation process is interactive. MDH starts by soliciting and evaluating information from various government agencies, the individuals or organizations responsible for the site, and community members living near the site. Any conclusions about the site are shared with the individuals, groups, and organizations that provided the information. Once an evaluation report has been prepared, MDH seeks feedback from the public. *If you have questions or comments about this report, we encourage you to contact us.*

Please write to:	Community Relations Coordinator Site Assessment and Consultation Unit Minnesota Department of Health 625 North Robert Street PO Box 64975 St. Paul, MN 55164-0975
OR call us at:	(651) 201-4897 *or* 1-800-657-3908 (toll free call - press "4" on your touch tone phone)
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Table of Contents

FOREWORD ..... **ii**
Table of Contents ..... **iii**
List of Tables ..... **iv**
List of Figures ..... **iv**
I. Introduction **2**
II. Background and Site History **3**
A. Split Rock Lighthouse 3
B. Concerns Related To Public Health 8
III. Chemicals of Interest **8**
A. Recommended Mercury Exposure Limits 8
1. Mercury Vapor Exposure 8
2. Dermal Exposure to Mercury-saturated Oil 11
B. Exposure To Mercury Vapor At Split Rock Lighthouse 11
1. Public Exposure 11
2. Occupational Exposure 13
IV. Discussion **13**
A. Mercury In Lighthouses 13
B. Factors Effecting Mercury Vapor Concentrations In Air 14
C. Uncertainties In Characterizing Mercury Exposures At Split Rock Lighthouse 14
Testing Conditions *14*
Mercury Spills *15*
Outdoor Mercury Vapor Concentrations *15*
D. Total Mercury Emissions From The Mercury Bearing 15
Mass Balance Model *15*
Mass Transfer Model *16*
Emission Modeling Results Summary *17*
E. Emissions While Servicing The Mercury Bearing 17
V. Summary and Conclusions **18**
VI. Recommendations **18**
VII. Public Health Action Plan **19**
VIII. Preparer of the Report: **19**
IX. References **20**
Appendix A: Mass transfer model calculations **22**
Appendix B: Mercury emissions during bearing servicing **24**
A. Ratio of surface area method 24
B. Exposure badge – ventilation method 25
CERTIFICATION **27**

List of Tables

Table 1: Split Rock Mercury Vapor Concentration Data (ng/m^3)....12
Table 2: Estimated Monthly Evaporation Rates, Bearing Loss 16
Table A-1: Monthly mercury vapor emissions....23

List of Figures

Figure 1: Split Rock Lighthouse Original Drawing 4
Figure 2: Split Rock Lighthouse Photos....5
Figure 3: Split Rock Lighthouse Historic Site 6

I. Introduction

For centuries lighthouses have been used to guide sailors or to warn them of dangerous rocks and shoals. Lighthouses in the late 1800s through the 1900s used rotating lenses around a light to flash a focused beam at recurring intervals. These flashes indicated, in code, the lighthouse identity. Therefore, it was critical to maintain the rotation speed of the lenses. Because the lens assemblies often weighed 2 or more tons, special bearings were required to support and rotate the lenses.

> "It has naturally been found impracticable to revolve the optical apparatus of a light with its mountings, sometimes weighing over 7 tons, at the high rate of speed required for *feux-éclairs* [lighthouses] by means of the old system of roller carriages, though for some small quick-revolving lights ball bearings have been successfully adopted. It has, therefore, become almost the universal practice to carry the rotating portion of the apparatus upon a mercury float. This beautiful application of mercury rotation was the invention of Bourdelles and is now utilized not only for the high-speed apparatus, but also generally for the few examples of the older type still being constructed. The arrangement consists of an annular cast iron bath or trough of such dimensions that a similar but slightly smaller annular float immersed in the bath and surrounded by mercury displaces a volume of the liquid metal whose weight is equal to that of the apparatus supported. Thus a comparatively insignificant quantity of mercury, say 2 cwt [200 lbs], serves to ensure the flotation of a mass of over 3 tons." (Encyclopædia Britannica, 1911)

Mercury evaporates very slowly. However, mercury vapors, when confined inside of a building, can reach high concentrations. As a result, emissions from mercury bearings in some lighthouses – or more probably from mercury spills in lighthouses - may have caused sickness in some lighthouse keepers and maintenance crews. Careless use and disposal of mercury can also lead to contamination of land and water, and to increased mercury levels in the atmosphere. Mercury in the environment can be converted into methyl mercury which can contaminate fish, especially predatory fish at the top of the aquatic food chain. Methyl mercury may impact the health of people who consume large amounts of predatory fish – especially the health of sensitive individuals including children and fetuses.

The widespread use of less expensive ways to warn ships has led to the decommissioning of many lighthouses. These alternatives include unmanned lights, buoys, LORAN (long range navigation), radar and, more recently, Global Positioning Systems (GPS). In addition, concerns about mercury sickness, as well as concerns about environmental contamination, led to the removal or replacement of some mercury bearings from lighthouses.

The Split Rock Lighthouse, a decommissioned lighthouse near Beaver Bay Minnesota, is one of the most visited lighthouses in the United States with over 100,000 visitors every year. The lens in the Lighthouse tower rotates on a mercury bearing that has been in place since the Lighthouse was built in 1910.

The Minnesota Historical Society (MHS), which administers and operates the Split Rock Lighthouse, asked the Minnesota Department of Health (MDH) to evaluate mercury exposures at Split Rock. This document is a review of the MDH evaluation of Split Rock mercury emissions and potential exposures to the public and people working at the site. MDH conducted this review under a cooperative agreement with the U.S. Agency for Toxic Substances and Disease Registry (ATSDR). MDH's and ATSDR's purpose is to serve the public by using the best science, taking responsive public health actions, and providing health information to prevent people from coming in contact with harmful toxic substances.

II. Background and Site History

A. Split Rock Lighthouse

Split Rock Lighthouse was commissioned in 1910 and operated by the US Lighthouse Service and the US Coast Guard until it was decommissioned in 1969. Some decommissioned lighthouses, including Split Rock Lighthouse, have been converted into historical sites or parks. The Minnesota Historical Society (MHS) took over administration of the Lighthouse in 1976 and has completely restored the Lighthouse. Today, whenever the lighthouse at Split Rock is open for visitors, the lens is rotated on the original mercury bearing by the original clockwork. In addition, the Lighthouse beacon lamp is lit a few times a month through the spring, summer and fall. The MHS is unaware of any other lighthouse in North America that has an operating mercury bearing.

The Split Rock Lighthouse sits on top of a 130 foot cliff, and the lens focuses a beam of light 168 feet above Lake Superior. The Split Rock Lighthouse has a Third Order Fresnel Lens mounted on a mercury bearing designed to rotate once every 20 seconds, with a 0.5 second flash every 10 seconds. A clock mechanism, below the bearing, drives the lens rotation. The lens assembly (lens, platform and pedestal, see Figures 1 and 2) weighs about 5000 pounds and floats on a mercury bearing that contains about 200 pounds (about 7 quarts) of mercury. Figure 1 is one of the original drawings of the bearing, bottom and top pedestals, clockworks and lens. Figure 2 shows a picture of the Lighthouse and 3 pictures of the lens room.

Figure 1: Split Rock Lighthouse Original Drawing

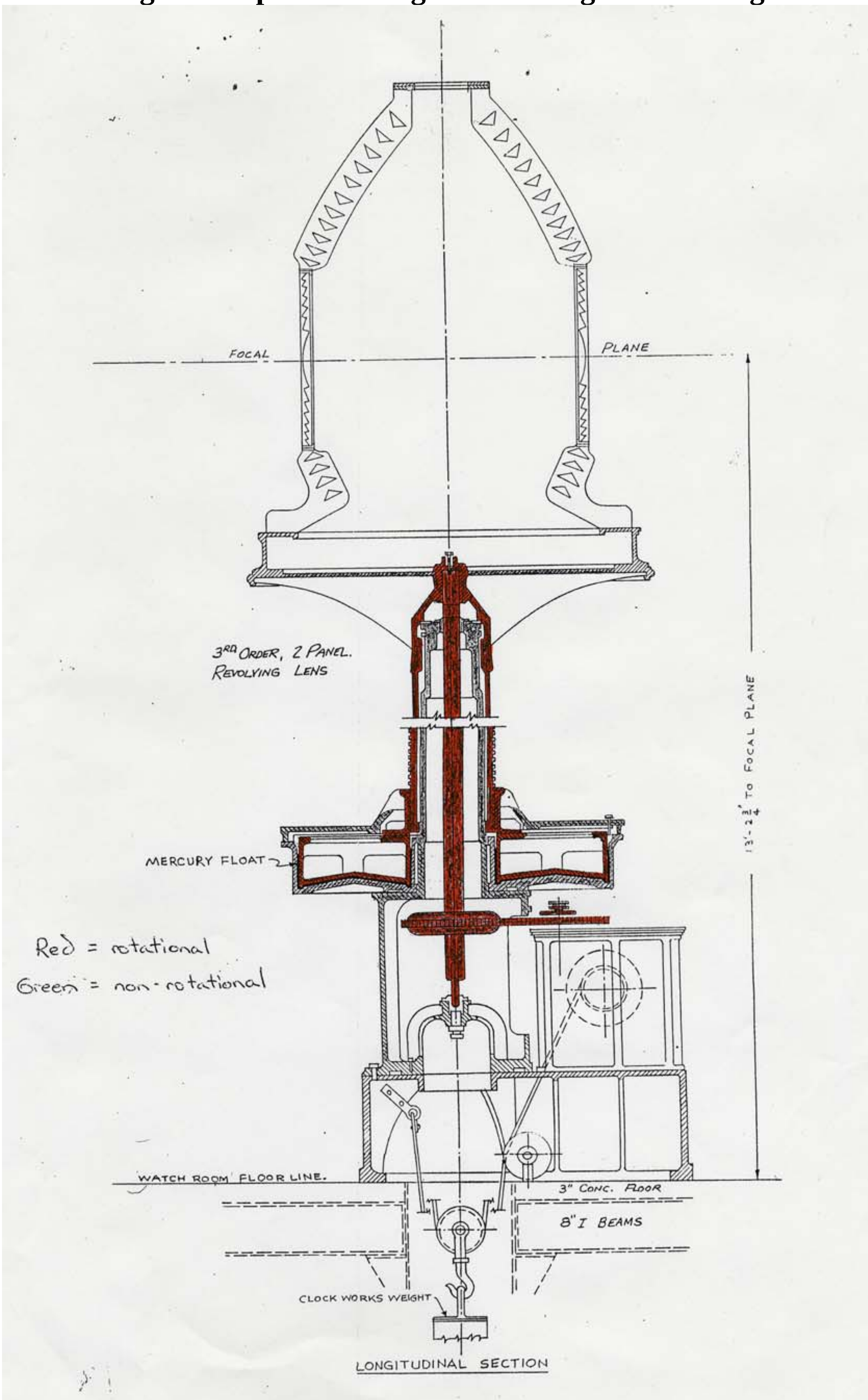
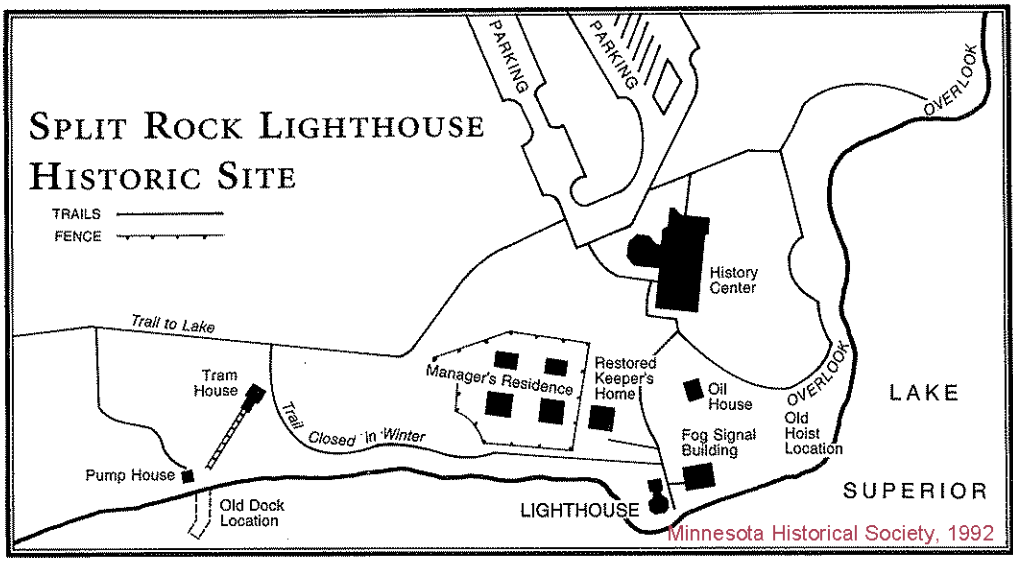


Figure 2: Split Rock Lighthouse Photos

MDH, 2004

Historic buildings at the Split Rock Lighthouse include the lighthouse, the fog signal building, an oil house, and 3 houses built for keepers' residences (Figure 3). Entry to the lighthouse is through a door on the northeast side of the cleaning room. The base of the tower is entered through a door from the cleaning room. The entire lighthouse has painted concrete floors and glazed brick walls. Windows in the lighthouse are used daily for ventilation, and the woodwork around the windows is varnished oak that is in excellent condition. The stairway from the base of the tower to the lens room is black painted metal. The lens room is entered through a doorway at the top of the stairs. There is no door in the doorway.

Figure 3: Split Rock Lighthouse Historic Site



The lens room is about 12 feet in diameter. In the center of the room is the mercury bearing that supports the light and lens. The bearing is about 52 inches in diameter and 11½ inches high and sits on a hollow pedestal 43¾ inches off the floor. The clock mechanism that rotates the lens is in the original steel framed glass box under the bearing, and the weights that run the clock are inside the hollow pedestal and the hollow shaft (weight-way) that runs through the floor of the lens room to the base of the tower. The lens and lamp sit on a pedestal that extends upward out of the center of the metal plate that covers the bearing. The bearing cover is fixed, but the pedestal rotates. A brass collar that rotates with the pedestal acts as a baffle, restricting access to the rotating bearing float. The lens platform is about 70 inches above the bearing. Above the lens, at the top of the tower is a vent that appears to be about 6-8 inches in diameter. This vent is covered by a baffle to keep rain and snow out, but it is always open to the outside. The location of this vent, at the top of the lighthouse tower, assists the movement of air from the bottom to the top of the lighthouse, decreasing the potential for mercury vapor from the bearing being drawn into the public areas of the lighthouse. Brass covered vents, about 1 foot off the floor around the lens room, and windows throughout the Lighthouse can be opened to increase ventilation. Ventilation was necessary when the lighthouse was operational, to keep the tower free of smoke from the burning lamp, and also to keep the tower at a comfortable temperature. An unintentional benefit has been that mercury vapor from the bearing and any spills are also vented, minimizing mercury vapor concentrations in the tower.

The 5000 pound lens assembly (Figure 1) floats directly on mercury. Floating a 5000 lb lens assembly on a pool of mercury requires displacement of an equal mass of mercury. However, the donut or concentric “Bundt cake-pan” design allows the bearing to float a heavy lens assembly with only a relatively small amount of mercury. The outside pan can hold over 5000 pounds of mercury, but because most of that mercury is displaced by the 5000 pound lens assembly float, only a small amount of mercury is needed in the bearing. This is comparable to floating a smaller glass in a tall, thin glass with only a small amount of water in the bottom. Even though the amount of water is small, the amount displaced by the inside (smaller) glass can be relatively large, and can be measured by the size of the impression the smaller glass makes in the water. The mass of water that would fill the impression is equal to the mass of the smaller glass.

The mercury bearing at Split Rock Lighthouse contains about 7 quarts or 200 pounds of mercury. While mercury supports the lens assembly, roller bearings maintain the vertical alignment of the assembly. Very small amounts of force can smoothly rotate huge lens assemblies on top of a mercury bearing. When operating, the Split Rock lens assembly was designed to rotate 3 times a minute, powered by a clock mechanism that needs to be wound every 2 hours by the lighthouse keeper.

In 1984 the lens rotation speed had dropped to about one rotation every 23 seconds. To restore the rotation speed, the mercury bearing reservoir was exposed by screwing the float up the threaded lens pedestal. A stopper plug on the bottom of the bearing casing was removed allowing mercury to be drained into a collection bucket. Historically, mercury drained from the bearing has been filtered through chamois. However, when mercury from the Split Rock bearing was removed in 1984 kerosene was mixed into the mercury. The metal particulates and oxides rose with the kerosene to the surface of the mercury and were then skimmed off. The mercury (about 200 lbs or 7 quarts) was then poured back into the top of the bearing, and the float was lowered into the bath, raising the lens assembly. The entire operation took 6.1 hours.

In September, 1985 lens rotation slowed from 22 seconds to about 27 seconds per rotation. About 1 pint of mercury was added at that time. A few years later, in the 1990s, motor oil was added on top of the mercury to decrease its oxidation and, possibly, to decrease the evaporation rate. Over the last few years the lens rotation has again slowed. Because the light no longer guides ships, this slowing is not critical. However, it does suggest that there is some added friction and increasing rotation resistance. This resistance could be caused by a loss of mercury, by metal flakes or mercury oxides, or other particulates in the bath that may impede rotation. According to the MHS, the increase in rotation period, as well as the twenty years since the last servicing, suggest that the bearing should be serviced.

The MHS manager of the Split Rock Lighthouse asked MDH for assistance in reviewing methods to safely service the mercury bearing. The manager has expressed to MDH that his primary concerns are the health and safety of the visiting public, and the health and safety of his employees. He also wants to assure that Lighthouse remains a historical site with the lens remains operational on the original bearing. Mercury vapor concentrations in the Split Rock Lighthouse have been measured by MDH and the Minnesota Pollution Control Agency (MPCA). The intent of this document is to review available data prior to bearing servicing, which is currently scheduled for November or December of this year (2009) – sometime after the Lighthouse closes to the public on November 11.

B. Concerns Related To Public Health

Mercury is the only metallic element that is a liquid at room temperature. Mercury evaporates extremely slowly, but in areas where ventilation is restricted, mercury vapor concentrations can reach levels of health concern. At Split Rock Lighthouse, exposures to mercury vapor above typical background concentrations are possible for both employees and the visiting public. This document reviews mercury vapor data from the Lighthouse and discusses whether these exposures could be hazardous.

An additional concern is that mercury emissions from a bearing contribute to the total amount of mercury that is released to the environment. Mercury vapor emitted into the atmosphere is eventually stripped from the air. Some enters the aquatic environment where it can be converted to methyl mercury. Methyl mercury is accumulated in biota and the concentration of methyl mercury in biota increases as it moves up the food chain. Fish, especially large fish at the top of the food chain (such as walleye, trout and northern pike), may accumulate methyl mercury at levels of concern for human consumption. This has caused public health agencies in Minnesota and nationally, to publish fish consumption advice (e.g. http://www.health.state.mn.us/divs/eh/fish/index.html, http://www.epa.gov/mercury/advisories.htm). It is beyond the scope of this document to evaluate the impact of mercury emissions from lighthouse mercury bearings on the environment or methyl mercury concentrations in fish. However, this document does provide a rough estimate of emissions for comparative evaluation.

III. Chemicals of Interest

A. Recommended Mercury Exposure Limits

1. Mercury Vapor Exposure

MDH mercury vapor exposure guidelines noted in this document are the same as guidelines used in previous MDH Health Consultations (2001; 2006; 2008). In addition, application of these criteria are discussed in an MDH memo to the Minnesota Pollution Control Agency (MPCA) January 30, 2007 (http://www.health.state.mn.us/divs/eh/hazardous/topics/mercury/vaporconc0107.pdf).

Direct public exposure to mercury vapor during a visit to Split Rock Lighthouse will be for a short duration. Exposure is likely limited to the time an individual spends in one or two areas inside the lighthouse. Therefore, it is appropriate to apply an acute mercury health criterion to ambient air mercury vapor concentrations inside lighthouses. Mercury vapor measurements in breathing zones (i.e. at elevations above the floor corresponding to the mouth/nose height of children and adults) should maintained below acute (1 hour average) health based levels.

MDH uses an acute mercury criterion of 1800 nanograms per cubic meter (ng/m^3) to evaluate short term mercury exposures of 1 hour per day. This number is adopted from the 1999 California Office of Environmental Health Hazard Assessment (CA OEHHA) Reference Exposure Level (REL) with a critical endpoint of reproductive or developmental effects (CA OEHHA, 2001). This REL was based on developmental effects in the offspring of exposed rats. Central nervous system effects in pups were noted following exposure of dams to 1.8 milligram per cubic meter (mg/m^3; 1 mg/m^3 = 1,000,000 ng/m^3) for 1 hour/day during gestation. A cumulative uncertainty factor of 1,000 is attached to this REL because it is based on a Lowest Observed Adverse Effect Concentration (LOAEC; 10x), the primary study was an animal study (10x), and human response to chemicals varies between people (10x). In 2008 OEHHA modified this REL, from 1800 ng/m^3 to 600 ng/m^3. This change in the REL was a result of changing the interspecies toxicodynamic uncertainty factor from $\sqrt{10}$ to 10, leading to an overall uncertainty factor of 3000 in the acute REL (CA OEHHA, 2008). MDH has not adopted this new criterion.

While MDH acute guidance should be applied to breathing zone concentrations, areas near the floor, or inside closets or cupboards, may exceed this acute criterion without engendering concern. Bulk mercury in an active lighthouse may have been handled, stored, and possibly spilled in any area in the lighthouse. Exceedance of the criterion in areas inaccessible to the general public will not result in an adverse exposure to visitors. However, hotspots of mercury contamination will increase exposures to mercury vapor in breathing zone air in nearby trafficked areas.

The Minnesota Occupational Safety and Health Administration (OSHA) sets legal limits for workplace exposures of individual with an expectation of on-the-job exposure to specific chemicals. (The Minnesota OSHA Standard allows an 8 hour per day time weighted average (TWA) exposure to mercury vapor up to 50,000 ng/m^3 without personal protection equipment.) However, in a number of instances, MDH has recommended safe exposure values for workers who have no expectation of exposure to hazardous chemicals on-the-job. It is not clear if MHS employees have an expectation of mercury vapor exposure at the lighthouse. If they have no expectation of mercury vapor exposure, then the MDH recommendations should be applied; otherwise, the MN OSHA value cannot be exceeded.

MDH uses the EPA chronic mercury reference concentration (RfC) when evaluating long term mercury exposures. RfCs are set to be protective of the most sensitive segment of the general public, excluding hypersensitive individuals. The most sensitive endpoint for mercury exposure in people has been shown to be developmental. Therefore, it is important that fetuses and young children not be exposed to long-term average concentrations above the RfC. While young children are not likely to be chronically exposed to mercury vapor in a lighthouse, pregnant women may be employed at a lighthouse and may be subject to chronic exposures at concentrations found in that lighthouse.

EPA's integrated risk information system (IRIS) database specifies an RfC for chronic exposure to mercury vapor of 300 ng/m^3 (U.S. EPA IRIS, 2003). The mercury RfC is derived from multiple studies of occupational exposures. The observed critical effects included hand tremors, increases in memory disturbances, and slight subjective and objective evidence of autonomic nervous system dysfunction.

The lowest observable adverse effects concentration (LOAEC) in the occupational studies converge at 25,000 ng/m^3. Affected workers had mean whole blood mercury concentrations of 10–12 micrograms per liter (µg/L). Adjusted to a 24 hour, 7 days per week exposure, the $LOAEC_{adj}$ = 9,000 ng/m^3. An uncertainty factor of 30 was applied to the $LOAEC_{adj}$ to arrive at an RfC that is assumed to engender no adverse effects. The uncertainty factor includes a factor of 10 for human variation in sensitivity, and a factor of 3 for lack of studies on the reproductive and developmental effects of elemental mercury. Because exposure at the lighthouse is limited to workweek exposures (and not to exposures 24 hours a day and 7days a week), the site-specific RfC should be calculated from an unadjusted LOAEC. Therefore, MDH recommends using a site-specific RfD of 800 ng/m^3 when evaluating the chronic hazard of mercury vapor to employees in lighthouses. The calculation of this RfC assumes that there is a threshold level for mercury exposure-related health effects.

The California OEHHA derived a chronic REL for inhalation exposure to mercury from the same studies used to develop the IRIS RfC. However, instead of using the cumulative uncertainty factor of 30 used by EPA, OEHHA has adopted an uncertainty factor of 300. This is based on a factor of 10 for the uncertainty of using an LOAEC exposure instead of a "no observable adverse effects concentration" (NOAEC) when calculating the REL; and also includes a $\sqrt{10}$ factor for human intraspecies toxicokinetic variability and 10 for intraspecies toxicodynamic variability (see Attachment 2). The California REL for mercury (elemental and inorganic) is 30 ng/m^3.

The Agency for Toxic Substances and Disease Registry (ATSDR) has a health-based minimum risk level (MRL) for mercury of 200 ng/m^3 (ATSDR, 2004). This MRL is calculated from the same data that was used to calculate the IRIS RfC. However, the MRL calculation assumes that in an occupational exposure, one third of the daily inhaled air each working day is contaminated. The RfC assumes that half of the working daily inhalation is contaminated.

Typically MDH uses IRIS RfCs for giving exposure advice when there is not a MDH Health Risk Value (HRV) for the chemical of interest. MDH has some concern that the EPA mercury RfC uncertainty factor of 30 may not sufficiently protect sensitive subpopulations given that the basis of the underlying value is an LOAEC. The California chronic mercury REL does provide this additional protection. However, practical application of the mercury REL at contaminated sites may be problematic because personal exposure to mercury from other sources, including dental amalgams, may be in the range of the REL. MDH therefore recommends that the EPA criterion be used when evaluating chronic public exposures. But care should be taken to ensure that chronic exposures to mercury from all sources do not exceed this level.

2. Dermal Exposure to Mercury-saturated Oil

Dermal exposure to elemental mercury is not typically a concern because elemental mercury, in droplet form, does not easily penetrate through the skin. However, dermal exposure to mercury vapor can be significant at high concentrations. Hursh et al. (1989) showed that dermal exposure to mercury vapor could result in uptake of about 2.2% of an inhaled dose. While dermal exposure to a droplet of mercury may not result in a large exposure, exposure to individual mercury vapor atoms may result in uptake. The reason for this difference in uptake is not apparent, but it could be because of differences between the physical/chemical properties of a mercury droplet and mercury vapor (e.g. high surface tension may change the uptake kinetics).

In the 1990's motor oil was put onto the surface of the mercury bearing at the Split Rock Lighthouse in an attempt to decrease mercury evaporation. The oil has become saturated with mercury. The saturation concentration of mercury in oil is not known. But it is likely that the saturation concentration in oil is much higher than the saturation concentration in air, when compared by volume or contact surface area. Furthermore, if dermal contact with the oil occurs, the oil may act as a vehicle, enhancing mercury penetration. Therefore, MDH is concerned that dermal contact with this oil might cause a dangerous mercury exposure.

B. Exposure To Mercury Vapor At Split Rock Lighthouse

1. Public Exposure

On April 30, 2001 the MPCA measured mercury vapor concentrations at Split Rock. On September 2, 2004 and August 15, 2009 MDH measured mercury vapor concentrations at Split Rock. Mercury vapor concentration data (measured with OhioLumex Company, Twinsburg OH, Mercury vapor analyzer, Model RA-915) are shown in Table 1. Note that the outdoor temperatures on all 3 days that testing occurred were very warm when compared with historic monthly temperatures. This suggests that the samples may represent worst case mercury vapor concentrations – when mercury volatilization is at a maximum. The morning of the August 15, 2009 visit, the (spot) temperature of the exterior of the bearing was measured at 74.8°F using an infrared temperature gauge (EXTECH Instruments, Waltham MA, High temperature infrared thermometer with laser pointer, Model 42545). This bearing temperature is similar to the outdoor average maximum temperature for Beaver Bay for the month of August (74.2°F; 2005-2008 Station 210564 Beaver Bay 5SW) and likely reflects the high temperatures that had prevailed at Split Rock over a few days proceeding testing.

Table 1: Split Rock Mercury Vapor Concentration Data (ng/m^3)

	April 30, 2001				September 2, 2004				August 15,2009 AM				August 15,2009 PM			
Recorded Daily Temperature (Beaver Bay, MN, MN State Climatology Office)	50-71° F				52-81° F				63-82° F							
Historic Daily Temperature Range (2005-2008)	30-47° F				45-65° F				54-74° F							
Sampling Period	10 second				10 second				30 second				30 second			
	Mean	(n)	Minimum	Maximum	Mean	(n)	Minimum	Maximum	Mean	(n)	Minimum	Maximum	Mean	(n)	Minimum	Maximum
Office Information Center	**~ 20**															
Outside	**~ 70-80**				**40**	(5)	1 *	69	**63**	(5)	46	78	**23**	(4)§	2 *	40
Cleaning Room	**673**	(6)	370	835	**1**	(1)	1 *	1 *	**36**	(2)	30	42	**9**	(2)§	7 *	10 *
Tower Base	**360**	(6)	309	445	**36**	(6)	1 *	70	**59**	(2)	39	78	**9**	(2)§	7 *	10 *
Tower Base Weight-way Manhole					161	(9)	48	326								
Tower Base 1/3 Up Stairs					**67**	(1)	67	67								
Tower Base 2/3 Up Stairs					**66**	(3)	65	67								
Bearing Room Closed Ventilation									2,708	(3)	2,080	3,129				
Bearing Room Normal Ventilation	**717**	(6)	384	1,100	**363**	(21)	163	856	**1,380**	(5)	958	1,852	**341**	(4)§	307	375
Bearing Room Weight-way	~ 50,000				7,252	(6)	1,951	15,230					3,080	(2)§	2,902	3,257
Bearing Room Above Float					13,831	(3)	4,017	30,070	2,145	(2)	1,842	2,448	831	(2)§	808	854
Bearing Room At Bearing Collar	~ 13,000				46,518	(9)	27,090	56,070 *	>50,000 *				33,290	(2)§	32,820	33,760
Bearing Room Below Lens Platform					673	(3)	614	709								
Bearing Room Inside Removed Collar					44,393	(3)	27,360	53,050 *								
Bearing Room Inside Keeper Locker					1,192	(3)	1,106	1,263								
Lens Platform Inside Lens					605	(3)	593	626								
Lens Platform Deck					877	(3)	620	1,134								
Oil House (oil room)	**~ 40-50**								**86**	(1)						
Inside Keeper House (#3)	~ 40-45								85	(1)						
Inside Cardboard Mercury Storage Box	~ 1500								1,813	(1)						
Inside Large Plastic Mercury Storage Box									4,073	(1)						

Data taken with RA 915 Mercury Vapor Analyzer, OhioLumex Company
Bolded data are mercury vapor concentrations that the public may be exposed to for a limited duration
* data outside of quantifiable detection range of instrument
§ data acquired using 2 different Lumex 915 Mercury Vapor Analyzers side-by-side

Note that none of the likely exposure values (bolded in Table 1) exceed the MDH acute (1 hour per day) criterion for mercury of 1800 ng/m^3. The highest potential exposure was 1,380 ng/m^3. This mercury vapor concentration (mean of 5 – 30 second readings) was recorded a few minutes after the windows in the tower were first opened and the lighthouse was first opened to the public. All of the data that exceed the acute criterion were taken when the analyzer intake was up against or very near to the brass baffle that covers the opening to the mercury bearing, in the weight-way, or prior to opening in the morning when the tower had been shut up over night. While it is conceivable that a tall person could lean over the bearing and take a breath or two above the float, the volume of air containing more than 1800 ng/m^3 is likely limited to less than a few breaths and therefore exposure would likely be less than 1800 ng/m^3 when averaged over a few minutes. A limitation is that these data characterize possible exposures on the days of the tests and may not reflect exposures on other occasions.

2. Occupational Exposure

As noted above, MDH recommends exposure to less than 800 ng/m^3 mercury vapor for daily, on-the-job occupational exposure of individuals who have no expectation of mercury exposure. Acute criterion for these individuals is the same as acute criterion for the general public; one hour average exposure less than 1,800 ng/m^3. From measured mercury vapor concentrations summarized in Table 1, it can be seen that exposure to either 800 ng/m^3 daily for an extended period, or exposure to 1,800 ng/m^3 for 1 hour are unlikely to occur, unless the lighthouse is not being ventilated, or the employee is involved in work that requires breathing in a small enclosed space in the lighthouse.

The two individuals who serviced the bearing in 1984 had an expectation of mercury exposure. These employees did not wear respirators while servicing the bearing. However, they did wear passive personal air sampling badges. Their exposures averaged 96,000 and 112,000 ng/m^3 for 6.1 hours each. This is considerably higher than the MN OSHA TWA of 50,000 ng/m^3.

Mercury-saturated oil was not present when the bearing was serviced in 1984. When the bearing is next serviced, the oil that covers the bearing may be an extremely hazardous waste, and no dermal exposure to this oil can be allowed.

IV. Discussion

A. Mercury In Lighthouses

There are about 117 commissioned lighthouses on the Great Lakes. In the 1960s the US Coast Guard addressed potential mercury contamination issues by removing most mercury bearings in lighthouses in the Great Lakes. Currently, no commissioned lighthouses in the Canadian Maritimes (Health Canada, 2003; Gauthier, 2004) or in the Great Lakes (US or Canadian) (U.S. Coast Guard, 2004) have mercury bearings. In addition, MDH has been unable to identify any decommissioned lighthouses, other than Split Rock, with mercury bearings on the Great Lakes. Furthermore, according to a lampist who was involved in removing mercury bearings from service while he was in the Coast Guard, Split Rock is the only remaining operational mercury bearing anywhere in the United States (Pepper, 2009).

The amount of mercury spilled at lighthouses, or the frequency of spills is not known. Historically, there was not a good understanding of the potential health effects of long term exposure to mercury vapor, and mercury spills were not a big concern. In 1938 an earthquake at the Kalaupapa Lighthouse in Hawaii caused a spill of about 200 lbs (7 quarts) of mercury from a bearing (Dean, 1989). Apparently, there were no reports of health effects from this spill. It is likely that health effects from mercury exposure at lighthouses were rarely reported, because mercury vapor toxicity was not well understood at the time. However, even following a cleanup of visible mercury from a spill, high exposures can occur. A spill of about 40 kilograms (3.1 quarts) caused by an earthquake at Rottnest Lighthouse in Australia in 1979 was cleaned up, yet months after the spill, the keeper and his wife suffered from mercury poisoning (White, 2004).

A study of a lighthouse with a mercury bearing on the Canadian west coast in 1986 showed mercury vapor concentrations in the lighthouse from 4,400 – 26,300 ng/m^3 (van Netten and Teschke, 1988). Families at this lighthouse lived in homes that were not attached to the lighthouse, so exposures were somewhat limited. Urinary mercury concentrations for the keepers and their spouses ranged from no detection (< 1.8 μg/l) to 3.0 μg/l. Comparison of these data with the geometric mean and 95th percentile concentrations of urine mercury for U.S. women aged 16–49 years (0.72 and 5.00 μg/L, respectively; in the 1999–2000 National Health and Nutrition Examination Surveys; US Department of Health and Human Services, 2005) suggest that the keeper family exposures in this lighthouse were not above the range of mercury exposure levels found in the U.S. population. However while these specific families did not appear to be impacted by mercury exposure, van Netten and Teschke (1988) suggest that mercury exposure may have been a contributing factor in some of the more bizarre incidents of violent and odd behavior in lighthouse keepers.

More recent concern about mercury exposures has led to closing some lighthouses to the public (e.g. Miscou lighthouse, New Brunswick, Canada), and the removal or replacement of mercury bearings from other lighthouses (e.g. Hillsboro Inlet Lighthouse, Florida; Point Arena Lighthouse, California).

Mercury vapor concentration data from the Split Rock sampling event on April 30, 2001, may suggest that there have been spills at the Lighthouse (note elevated Tower Base and Cleaning Room samples in Table 1). However, the data from more recent sampling events suggest that emissions from historic spills and mercury volatilization from the mercury bearing is not serious at this time.

B. Factors Effecting Mercury Vapor Concentrations In Air

Mercury evaporates very slowly. Therefore, ventilation is an effective way to decrease mercury vapor concentrations inside of a building. Mercury evaporation rate is highly temperature dependant. For every 2°C rise in temperature, the mercury vapor pressure increases about 20% (or expressed another way, vapor pressure doubles about every 7½°C). Therefore, at low temperatures less ventilation is needed to keep mercury vapor concentrations below levels of concern. It is likely that when the temperature inside the lighthouse, in particular the temperature of the bearing, walls and floors of the lighthouse are below 55°F (12.8°C) for example, passive ventilation through the roof vent with closed windows will be sufficient to keep the mercury concentration throughout the lighthouse below levels of concern. As the temperature rises, additional ventilation is needed to keep mercury vapor from accumulating to levels of concern.

C. Uncertainties In Characterizing Mercury Exposures At Split Rock Lighthouse

Testing Conditions

All 3 sampling days were warm and sunny. If the windows are not opened on cool sunny days when the sun warms the inside of the lighthouse, it is possible that there could be higher exposure concentrations. Indoor air mercury vapor concentrations under these conditions may be similar to data gathered prior to ventilation on August 15, 2009. This can be avoided by maintaining ventilation even when the outside temperatures are chilly or by assuring that the mercury bearing temperature is 55°F or below when the windows are shut.

Mercury Spills
Over the years of active service, it is likely that there were some mercury spills in the lighthouse and other areas of the Split Rock facility. The residues from mercury spills can offgas mercury for many years after a spill, so exposures to historic spills is a possibility in any area where mercury is handled. Data from 2001 (Table 1) suggest that there were remnants of spills offgassing mercury in the base of the tower and the cleaning room. Apparently, the mercury from these spills have either been cleaned or encapsulated under paint since 2001. There do not appear to be data suggesting additional spills inside of buildings at Split Rock Lighthouse.

Outdoor Mercury Vapor Concentrations
Typical outdoor mercury vapor concentrations are about 2 ng/m^3. This is often considered the global background mercury vapor concentration. Table 1 shows that the outdoor mercury vapor concentrations were considerably higher than this, in the range of 20 – 80 ng/m^3. This is not particularly surprising. MDH and MPCA staff have noted at other locations that mercury vapor concentrations, near the ground, appear to be well above "background" levels during daytime hours. This seems to be especially true in areas where the sun is bright. It is known that ultraviolet radiation stimulates the release of mercury vapor from soil and vegetation (Moore and Carpi, 2005). In addition, it has been postulated that ozone, which is found at much higher concentrations during daylight hours, also stimulates the release of mercury from soil and vegetation (Zhang et al., 2008). Generally, there appears to be a diurnal pattern to mercury vapor concentrations in air, with high concentrations in the morning, followed by decreasing concentrations through the afternoon and night (Stamenkovic et al., 2007; Watras et al., 2009). Mercury vapor concentrations at different elevations above the ground, or at different times of the day and night, may be quite different than those shown in Table 1. Regardless, exposures to mercury vapor at concentrations measured outdoors at Split Rock are insignificant when compared to mercury exposure criteria.

D. Total Mercury Emissions From The Mercury Bearing

There are two ways to estimate the mercury emissions using available data. The amount of mercury in the bearing at two different times may be estimated and compared (mass balance estimation); or an emission rate can be calculated from a theoretical mercury evaporation rate, estimates of the bearing temperature, estimates of the surface area of exposed mercury, and assumptions of the air concentrations near the surface of the bearing.

Mass Balance Model
In 1985 the rotation speed of the mercury bearing slowed, and now, in 2008-9 it has slowed again. When the rotation slowed in 1985, about 1 pint of mercury was added to the bearing, restoring rotation to the proper speed. If the mercury level in the bearing prior to adding 1 pint in 1985 and the mercury level in the bearing today are the same, the loss by volatilization could be assumed to be about 1 pint in 24 years, about ½ pound of mercury per year, or 720 mg/day. However, the amount of mercury added in 1985 was

not well documented and was estimated. Further, it is not known if the recent slowing of the bearing is due to loss of mercury, oxidation of mercury, or buildup of grit or sludge in the bearing.

Mass Transfer Model
Split Rock mercury bearing emissions can also be estimated using a calculated mercury vaporization rate, site-specific temperature data and the surface area of the bearing. This is described in greater detail in Appendix A.

The mass transfer model assumes that mercury transfer velocity from the surface of a mercury pool is similar to the air phase mass transfer velocity of water, adjusted for the lower rate of diffusion of mercury. Model results are shown in Table 2. Note that the estimated evaporation rate for June is similar to 20°C evaporation rates published in the literature (7 $\mu g/cm^2/hr$, Andren and Nriagu, 1979; 7 $\mu g/cm^2/hr$, Riley et al., 2001; 8.8 $\mu g/cm^2/hr$, Bigham et al., 2008).

Table 2: Estimated Monthly Evaporation Rates, Bearing Loss

	Temperature Average Maximum*		Mercury Saturation	Evaporation Rate	Bearing Loss
	°F	°C	$\mu g/m^3$	$\mu g/cm^2/hr$	g/month
January	24	-4.7	1,300	0.65	0.14
February	23	-5.0	1,300	0.62	0.12
March	36	2.0	2,700	1.3	0.27
April	47	8.6	4,900	2.4	0.48
May	56	13.2	7,400	3.6	0.76
June	68	20.2	13,000	6.5	1.3
July	75	23.8	18,000	8.7	1.8
August	74	23.5	18,000	8.5	1.8
September	65	18.5	12,000	5.6	1.1
October	53	11.4	6,300	3.1	0.65
November	39	3.7	3,100	1.5	0.31
December	25	-4.0	1,400	0.69	0.15

* 2005 – 2009 average daily high temperature National Weather Service Station 210564 Beaver Bay 5SW

The screening model assumes that the air above the mercury surface is being replaced constantly, and that the temperature of the bearing is similar to the average daily maximum outdoor temperature in Beaver Bay (range: -5.0°C, in February, to 23.8°C in July). (Note: the Beaver Bay Weather Station is located about 5 miles inland from Lake Superior. Therefore, temperatures at the Weather Station are not moderated by the Lake to the same extent that temperatures at the Lighthouse are moderated.) These emission estimates should be considered to be "back-of-envelope" estimates, developed to help plan any future testing at this site. The mercury vaporization rate was calculated to be 0.6 $\mu g/cm^2/hr$ in January, and 9 $\mu g/cm^2/hr$ in July. Assuming a bearing surface area of 355 cm^2 (estimated from bearing drawings and dimensions), total emissions were calculated to be 9 g/year (0.02 lbs/year). This is equivalent to 0.7 milliliters (ml) per year (0.13 teaspoons per year) and averages about 25 mg/day mercury emissions. For comparison, average daily mercury emissions are about the same as the amount of mercury found in 6 compact fluorescent bulbs.

Emission Modeling Results Summary
Total mercury emissions from Minnesota in 2000 were estimated at 3,638 lb (MPCA, 2004). All the coal fired power plants in Minnesota together emit about 1,500 pounds of mercury a year; and individual dentists typically use about 1 lb mercury per year in dental amalgams (MPCA, 2001). The MPCA evaluates mercury emissions in Minnesota and determines state priorities and policies related to mercury emissions.

Both of these models for mercury loss (mass balance and mass transfer models) are rough. The mass balance model estimates emissions to be about 30 times the mass transfer model emissions. All of the information and assumptions used in the mass balance estimate are uncertain, and could either overestimate or underestimate emissions. On the other hand, the mass transfer model would be expected to over estimate the mercury emissions from the bearing because mercury vaporization rate is less than the calculated maximum rate given that the presence of mercury vapor in the air immediately above the liquid mercury will slow volatilization. Therefore, the mercury emission rate is likely considerably less than the theoretical evaporation rate and is a function of the volume of air flowing from the bearing at the baffle. Because the mass transfer model likely overestimates the emissions, and the mass balance model estimates much higher emissions than the mass transfer model, the mass balance estimates are probably in error.

Oxidation of mercury exposed to air slows mercury evaporation. Oxidation is also thought to be the main cause of increased rotational resistance of the bearing. A layer of oil on top of the mercury bearing, such as the one applied to the Split Rock bearing in the 1990s, could slow the oxidation of mercury that is exposed on the top of the bearing (McKeehan, 1916). As a result, covering the bearing with oil could increase the time between bearing servicing, but also keep mercury loss rates constant over time. However, the impact of covering the mercury bearing with a layer of motor oil on total mercury emissions has not been well characterized. Another option that might decrease evaporation and oxidation more effectively than a layer of oil would be to enclose the bearing in a non-oxidizing environment. This would require the installation of an air seal and displacement of air covering the bearing with a non-reactive or inert gas.

E. Emissions While Servicing The Mercury Bearing

Appendix B discusses different ways of estimating mercury emissions during bearing servicing. When emissions are calculated using a ratio of the surface area of the exposed bearing at 4 - 10° C to the surface area of mercury in the operating bearing, emissions during servicing are estimated to be 4-7% of the yearly emissions. This does not include emissions from materials used and contaminated during servicing (e.g. containers, rags, dropcloths, tools). Alternatively, emissions can be calculated using the mercury vapor concentrations recorded on the air sampling badges during the 1984 sampling and a calculated ventilation rate. This method suggests that emissions during servicing are about the same as ½ of the yearly emissions from the bearing. The difference between the temperature when the bearing was serviced in 1984 and the temperature when the bearing is next serviced, and likely differences in ventilation rates, are not incorporated into this estimate.

V. Summary and Conclusions

Split Rock Lighthouse is one of the most visited tourist destinations in Minnesota, and one of the most visited lighthouses in the United States. Split Rock Lighthouse may be the only lighthouse in the Great Lakes and the United States to have a functional mercury bearing. Review of mercury vapor concentration data in the Lighthouse suggests that the Lighthouse managers have kept the interior of the lighthouse clean and free from mercury contamination.

MDH and ATSDR conclude that mercury from the bearing at Split Rock Lighthouse is not expected to harm people's health when normal or recommended operating procedures are followed. In addition, it is likely that the exposure to regular employees of the historic site also presents no apparent health hazard. These conclusions are drawn from evaluation of data from 4 sampling events on 3 days. However, data demonstrate that passive ventilation through open windows and vents is necessary to maintain acceptable mercury vapor concentrations in the lens room.

Exposure to workers servicing the bearing could present a health hazard if appropriate personal respiratory and dermal protection are not used. MDH is especially concerned about the potential dermal toxicity of the oil that currently covers the mercury bearing.

Initial rough estimates suggest that mercury vapor emissions from the bearing are less than 10 grams per year. Additional mercury emissions may occur from historic mercury spills around the site, but public indoor areas of the site do not show evidence of significant spills or releases. Emissions during servicing of the mercury bearing significantly contribute to the overall emissions from the Lighthouse.

VI. Recommendations

MDH recommends:

- Windows and vents in the lighthouse are kept open during visiting hours whenever the temperature in the lighthouse, or the temperature of the bearing, is above 55°F.
- MPCA consider evaluating the mercury vapor emissions from the Lighthouse to determine the effect on the local, regional and statewide mercury budget.
- Methods, other than covering the bearing with oil, should be considered to decrease oxidation of mercury on the surface of the bearing while maintaining low mercury vapor emissions.

MDH does not regulate the exposures of individuals working with chemicals and those having an expectation of exposure on the job. However, mercury exposures such as those that occurred during the last bearing servicing should be avoided. If the bearing is serviced in the future, MDH recommends that considerable effort be directed toward reducing the associated mercury exposures. Specific recommendations related to servicing the bearing:

- MPCA Emergency Response and/or Hazardous Waste experts should be consulted prior to servicing the bearing.
- The oil that covers the bearing may be extremely toxic and measures should be taken to assure that there is no dermal contact with any of this oil.

- The effect of covering liquid mercury with oil should be characterized prior to servicing the mercury bearing, to determine if:
    - oil decreases oxidation on the surface of the bearing
    - oil decreases mercury emissions
- Respirators should be worn when servicing the mercury bearing.
- Mercury and any materials contaminated with mercury should not touch the lighthouse structure, any external part of the bearing, or any other part of the permanent exhibit.
- Mercury vapor monitoring should confirm that there is no mercury contamination following servicing, and that mercury vapor exposures to the general public remain below levels of concern.

VII. Public Health Action Plan

MDH will assist the Minnesota Historical Society in evaluating any possible changes to mercury exposures that may occur at this site in the future. In addition, MDH will assist the Minnesota Pollution Control in measuring and modeling emissions from the Lighthouse to the environment, and in determining if there are potential impacts from site mercury emissions.

VIII. Preparer of the Report:

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Appendix A: Mass transfer model calculations

A rough screening estimate of emissions (mercury flux) from the Split Rock Lighthouse mercury bearing can be calculated as follows (Schwarzenbach et al., 2003):

$Ev_{Hg} = v_{water\ a} * C_{eq\text{-}air} * (AW_{Hg} / AW_{water})^{-1/3}$ *Equation A-1.*

{ug/cm^2/hr = m/s * μg/m^3 * m^2/10,000cm^2 * 3600s/hr}

Where: Ev_{Hg} = mercury evaporation rate
$v_{water\ a}$ = air-phase transfer velocity of water ($3.0*10^{-3}$ m/s)
$C_{eq\text{-}air}$ = mercury saturation concentration in air
AW_{Hg} = atomic weight of mercury
AW_{water} = atomic weight of water

The mercury saturation concentration in air ($C_{eq\text{-}air}$) is a function of the temperature and the mercury vapor pressure.

$C_{eq\text{-}air} = p_{vap\text{-}Hg} / (R * T)$ *Equation A-2.*

{μg/m^3 = mmHg / (Pa*m^3*mol^{-1}*°K^{-1} * °K) * 133.32 Pa / mmHg * 200.6*10^6 μg/mol }

Where: $p_{vap\text{-}Hg}$ = mercury vapor pressure
R = gas constant
T = temperature in °K

The mercury flux is equal to the evaporation rate applied over the surface area of the bearing.

$F_{Hg} = Ev_{Hg} * A$ *Equation A-3.*

{ μg/hr = ug/cm^2/hr * cm^2 }

Where: F_{Hg} = mercury flux
A = surface area of the mercury in the bearing exposed to air

For the purpose of modeling emissions, the area of mercury that is exposed to air on the surface of the bearing was assumed to be two 0.2 inch concentric circles at 22 inch and 47.6 inch diameters. This is equivalent to a surface area of 55 cubic inches or 355 cm^2.

Table A-1 shows the calculated results from *Equations A-1* through *A-3* for monthly average daily maximum temperatures recorded for Beaver Bay, MN.

Table A-1: Monthly mercury vapor emissions

	Temperature Average Maximum*		Mercury Vapor Pressure **	Mercury Saturation	Evaporation Rate	Mercury Flux
	°F	°C	Pa	µg/m^3	µg/cm^2/hr	g/month
January	23.6	-4.65	0.0148	1,335	0.65	0.136
February	23.1	-4.97	0.0143	1,291	0.62	0.119
March	35.6	1.98	0.0303	2,662	1.29	0.272
April	47.4	8.56	0.0568	4,867	2.36	0.481
May	55.8	13.20	0.0879	7,410	3.59	0.757
June	68.4	20.21	0.1628	13,400	6.49	1.325
July	74.8	23.79	0.2218	18,039	8.73	1.843
August	74.2	23.46	0.2160	17,586	8.51	1.797
September	65.3	18.50	0.1400	11,589	5.61	1.146
October	52.6	11.44	0.0748	6,344	3.07	0.648
November	38.6	3.68	0.0358	3,120	1.51	0.308
December	24.8	-3.98	0.0159	1,427	0.69	0.146

* 2005 – 2009 average daily high temperature National Weather Service Station 210564 Beaver Bay 5SW

** Interpolated from data in CRC (1969)

Appendix B: Mercury emissions during bearing servicing

A. Ratio of surface area method

An initial estimate of the mercury emissions from the areas of the bearing normally covered with mercury during servicing can be made using certain assumptions. For this estimate it is assumed that: the mercury evaporation rate from the mercury-exposed surfaces of the bearing is similar to the evaporation rate from the mercury exposed while the bearing is operational; all bearing surfaces are presumed to be exposed for 6.1 hours during servicing. The surface area of exposed mercury during normal lighthouse operation is about 355 cm^2, as noted in Appendix A. A donut-shaped float, supporting the lens weighing 5000 lbs, having an internal diameter of 22.4 inches and an external diameter of 47.6 inches, displaces about 7.3 inches of mercury:

$D_{float\text{-}vert} = M_{float} / Hg_{sp\text{-}grav} / A_{float\ c\text{-}s}$ *Equation B-1.*

$\{ \text{in} = \text{lbs} / 0.4913\ \text{lb/in}^3 / (\pi * (\text{in}^2 - \text{in}^2)) \}$

Where: $D_{float\text{-}vert}$ = vertical float displacement into the bath
M_{float} = mass of the float
$Hg_{sp\text{-}grav}$ = the specific gravity of mercury (0.4913 lb/in^3)
$A_{float\ c\text{-}s}$ = horizontal cross-sectional area of the submerged float

$7.345\ \text{in} = 5000\ \text{lbs} / 0.4913\ \text{lb/in}^3 / (\pi * ((47.6\ \text{in}/2)^2 - (22.4\ \text{in}/2)^2))$

For bearing emissions during operation it was assumed that the gap between the fixed pedestal and the float was 0.2 inches on both the inside diameter and the outside diameter of the mercury bath. When these clearances are assumed and 7 quarts is assumed to be the total amount of mercury in the bearing, the elevation of the float above the bottom of the bath can only be 0.057 in.

$C_{vert} = (V_{bath} - D_{float\text{-}vert} * A_{float\ c\text{-}s}) / A_{bath\ c\text{-}s}$ *Equation B-2.*

$\{ \text{in} = (\text{qts} * 57.75\ \text{in}^3/\text{qt} - \text{in} * \pi * (\text{in}^2 - \text{in}^2 + \text{in}^2 - \text{in}^2)) / (\pi * (\text{in}^2 - \text{in}^2)) \}$

Where: C_{vert} = vertical clearance between the bath and the float
V_{bath} = bath volume
$A_{bath\ c\text{-}s}$ = horizontal cross-sectional area of the bath

$0.057\ \text{in} = (7\ \text{qts} * 57.75\ \text{in}^3/\text{qt} - 7.345\ \text{in} * \pi * ((48\ \text{in}/2)^2 - (47.6\ \text{in}/2)^2 + (22.4\ \text{in}/2)^2 - (22\ \text{in}/2)^2)) / (\pi * ((48\ \text{in}/2)^2 - (22\ \text{in}/2)^2))$

Therefore, the total surface area of the bearing that is exposed to mercury is:

$SA_{ttl} = A_{float\ id} + A_{float\ od} + A_{float\ c\text{-}s} + A_{bath\ id} + A_{bath\ od} + A_{bath\ c\text{-}s}$ *Equation B-3.*
$\{ cm^2 = (in^2 + in^2 \ldots) * 6.4516\ cm^2/in^2 \}$

Where: SA_{ttl} = total area in contact with mercury during normal operation
$_{id}$ = inside (minor) diameter
$_{od}$ = outside (major) diameter

Float: $3001\ in^2 = \pi * (7.345\ in * (22.4\ in + 47.6\ in) + ((47.6/2)^2 - (22.4/2)^2))$
Bath: $\underline{3057\ in}^2 = \pi * (7.345\ in + 0.057\ in) * (22\ in + 48\ in) + ((48/2)^2 - (22/2)^2))$
Total: $6058\ in^2 * 6.4516\ cm^2/in^2 = 39084\ cm^2$

During the previous bearing servicing event in 1984, all surfaces of the bearing were exposed for less than 6.1 hours. Currently, the intent is to service the bearing in November. The mean daily high temperature for November is 38.6°F (3.68°C). At this temperature the mercury emission rate would be expected to be about 1.5 $\mu g/cm^2/hr$ (Table A-1). Total emissions during servicing would be expected to be 0.36 grams:

$E_{ttl} = Ev_{Hg} * SA_{ttl} * t$ *Equation B-4.*
$\{ g = \mu g/cm^2/hr * cm^2 * hr * 0.000001\ g/\mu g \}$

Where: t = time
$0.360\ g = 1.51\ \mu g/cm^2/hr * 39084\ cm^2 * 6.1\ hr$

If the temperature of the bearing during servicing is 50°F (10°C), the emission rate would be increased by about 80% ($Ev_{Hg} = 2.697\ \mu g/cm^2/hr$), increasing the total emissions proportionally ($E_{ttl} = 0.643$ g).

Comparing emissions calculated with this model to the total annual calculated emissions from the bearing (8.98 g) suggest that servicing the bearing will result in emissions equivalent to 4-7% of the total annual mercury emissions from the bearing. This estimate is a low estimate of the total mercury emissions during servicing, because the model does not include any mercury emissions from rags, dropcloths, tools, containers, the oil covering the bearing, mercury that is drained from the bearing and filtered waste. It is likely that emissions from these sources would be at least as large as the emissions from the surfaces of the bearing. The amount of mercury that is released from these other sources during servicing would be affected by their handling and disposal.

B. Exposure badge – ventilation method

Equation A-1 can be used to estimate emissions during servicing, if a ventilation rate and an exposure concentration are assumed. Ventilation rate with the windows open can be estimated from August 15, 2009 data.

At steady state, when the concentration of mercury in air is constant, the amount of mercury emitted by the bearing (flux) will be the same as the amount of mercury that is removed through ventilation plus the amount of mercury removed by sorption to surfaces or penetration into materials:

$$F_{Hg} = [Hg_{air}] * (V_{rate} + k) \qquad \textit{Equation B-5.}$$

$$\{ \mu g/hr = ng/m^3 * (cfm + cfm) * 0.001 \mu g/ng * 0.02832 m^3/ft^3 * 60 min/hr \}$$

Where: $[Hg_{air}]$= mercury vapor concentration in air
V_{rate} = known ventilation rate
k = unknown concentration-dependent loss (e.g. sorption, penetration, passive ventilation)

Mercury vapor concentrations in the Lens Room on August 15, 2009 with the windows open averaged 341 ng/m^3 (Table 1). Converting the calculated evaporation rate for August (Table A-1) to mercury flux and substituting into *Equation B-5* estimates the ventilation with the windows open plus sorption (V_{rate} + k) to be equivalent to about 4200 CFM.

If the windows open ventilation rate calculated from 2009 (very light breeze; 4200 cfm) and the mean exposure badge readings from 1984 (104,000 ng/m^3) are substituted into *Equation B-5*, emissions (F_{Hg}) are estimated at 750,000 µg/hr, for a total emission of about 4.5 g of mercury during the 6.1 hour operation. This is about ½ of the calculated yearly emissions from the bearing. This model assumes that the ventilation during the 1984 servicing was similar to the ventilation during the mercury vapor sampling event in August 2009.

CERTIFICATION

This Split Rock Lighthouse Health Consultation was prepared by the Minnesota Department of Health under a cooperative agreement with the Agency for Toxic Substances and Disease Registry (ATSDR). It is in accordance with approved methodology and procedures existing at the time the health consultation was begun. Editorial review was completed by the Cooperative Agreement partner.

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The Division of Health Assessment and Consultation, ATSDR, has reviewed this public health consultation and concurs with the findings.

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