Investigation of CFL Mercury Safety Issues: Preliminary Results

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Executive Summary

On behalf of Natural Resources Canada, the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute investigated the health effects of mercury exposure from broken compact fluorescent lamps (CFLs) in a residential or office context. The LRC primarily performed this investigation through a review of the literature and interviews with experts. The LRC also conducted laboratory-based photometric testing of some CFLs to determine the effect of an outer bulb on the efficacy of CFLs. Recent studies show that when bare spiral CFLs with liquid mercury (which are the "worst case" for mercury release) are broken, both acute (short term) and chronic (long term) mercury vapor exposure levels are below widely used limits, such as the standards set by the US EPA and the provisional standard set by Health Canada. Certain CFL features such as shatter-proof silicone coatings, glass or polymer outer coverings, and amalgam-based mercury can reduce the risk of breakage and/ or reduce mercury release upon breakage. The LRC found that Health Canada's present recommended CFL clean up procedures are consistent with the literature regarding best practices.

Background

The risk of mercury contamination from a broken compact fluorescent lamp (CFL) has been a concern of the general public for many years. Some events in the CFL market have prompted Natural Resources Canada (NRCan) to revisit the mercury issue:

- Recent claims by some CFL manufacturers that their mercury amalgam lamps are a "safer" alternative to liquid mercury-based lamps
- Testing that has indicated that covered CFL products have a significantly lower risk of mercury release when dropped than bare CFLs
- A reduction in recent years of the amount of mercury used in the manufacture of CFLs

NRCan contracted with the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute in Troy, New York, USA, to investigate this issue. The goal of this research project was to answer two questions:

1. Should it be recommended to Canadian citizens to purchase certain types of CFLs, such as amalgam and/ or covered CFLs, based on safety and performance characteristics?
2. Based on the health risks associated with breaking a CFL lamp, is it appropriate to reduce or simplify the currently recommended CFL clean up procedures (regardless of mercury type used in the lamp)?

The present study is designed as the first of up to two phases. This first phase involves laboratory-based photometric testing of some CFLs currently available on the Canadian market, a literature review, and interviews with experts. (The original scope of work for the first phase also included a poll of the public to learn about the temperature and age of CFLs when they are typically broken, but this task was eliminated when it became apparent that the results would not influence recommendations made to Canadian citizens.) At the conclusion of this first phase, the LRC will recommend to NRCan whether a second phase of research is needed, which could include laboratory measurements of mercury release from broken CFLs.

This report summarizes the LRC's findings of the first phase of the investigation and concludes with recommendations to NRCan about continuing with a second phase and if new data indicates that NRCan should modify its recommendations to Canadian citizens regarding the purchase of CFLs or cleaning them up upon breakage.

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- Heinz Ito, Manager NAFTA CFLi Development, OSRAM SYLVANIA General Lighting
- Horacio Trevino, GTD CFL-I/NI Section Manager, Philips Lighting Company
- Todd Crawford, Research Scientist 2, New York State Department of Health
- Patricia Fritz, Research Scientist, New York State Department of Health

The Use of Mercury in CFLs

Fluorescent lamps, including CFLs, are a low-pressure gas discharge light source. They have a sealed glass tube that contains mercury (in vapor and liquid or solid amalgam form) and an inert buffer gas. Inside both ends of the tube are electrodes made of coiled tungsten coated with metal oxides. The CFL's ballast creates a large voltage across the electrodes to initiate an arc between them and then limits the current after the arc is established. The energy in the arc further vaporizes the available mercury and elevates electrons in mercury atoms to an excited state. When the electrons return to their rest state, photons are released in ultraviolet wavelengths. These ultraviolet photons are absorbed by the internal phosphor coating, which then re-emits photons in the visible spectrum. Based on this principal of operation, mercury is a necessary component of fluorescent lamps.

The primary design goal for CFLs is to control the mercury vapor pressure to maximize light output and therefore efficacy. (Serres & Taelman, 1993) The optimum mercury vapor pressure in CFLs is typically 0.6 to 2 Pa, but can be as high as 4 Pa. (Heidemann, Hien, Panofski, & Roll, 1993; Lankhorst & Niemann, 2000) CFLs with pure mercury use "modified bulb wall configuration control" of mercury vapor pressure in which a portion of the bulb is designed to be farther from the discharge than the rest of the bulb, which yields a cool spot, which in turn controls the vapor pressure.

The vapor pressure of liquid mercury is dependent only on temperature, so at operating temperature, the vapor pressure can be higher than the pressure range that is best for efficacy. To address this issue, mercury amalgams can be used instead of liquid mercury to control the mercury vapor pressure over a wider range of operating temperatures. An amalgam is similar to an alloy in that it contains a mixture of two or more metals.

The amalgams retain their shape (as described below as a flag or sphere) at all times, including during operation. The amalgams serve as a holder of mercury, with the amount of mercury freed from the amalgam dependent on the temperature. An ideal amalgam would provide the vapor pressure of pure mercury at room temperature, but limit mercury vapor pressure at operating temperatures. (Lankhorst, Keur, & Hal, 2000) Because no amalgam exists with these properties, and because amalgams increase the run up time of CFLs compared with pure mercury, in most cases two different amalgams are used within a CFL. One is an "auxiliary amalgam" or "amalgam flag" which holds most of the mercury when the lamp is off and cooled to ambient temperatures, but which releases it quickly when the lamp is turned on. The second is the "main amalgam" which regulates the mercury vapor pressure at operating temperatures.

The auxiliary amalgam has a lower mercury vapor pressure than the main amalgam at equal temperatures to permit the absorption of mercury when the CFL is off. When the CFL is turned on, the temperature increases and the mercury in the auxiliary amalgam is released and precipitates on the nearby bulb wall. As the bulb wall near the electrode heats up, this mercury then vaporizes. The auxiliary amalgam is often made of an indium layer on a metal flag located near an electrode for fast heating. (Serres & Taelman, 1993)

When the CFL is at operating temperature, the vapor pressure is held relatively constant by the main amalgam absorbing some mercury. The mercury vapor pressure has a plateau in the temperature range when the solid and liquid phases of the formed amalgam coexist. Different main amalgams can be used in different CFL products, with the exact composition held proprietary to each manufacturer. Examples include indium-silver-mercury, indium-tin-mercury, bismuth-indium-mercury, and bismuth-lead-silver-mercury. (Lankhorst & Niemann, 2000) The mercury vapor pressure is a function of the amalgam used, the cold spot temperature, and the mercury concentration (weight-percent). (A. Corazza, Giorgi, & Massaro, 2011a) A small sphere of the main amalgam is usually located in the exhaust tube in the CFL base.

In addition to the auxiliary flag and main amalgams, two more metal mixtures may be used for the manufacturing and quality control of CFLs. One of these is a dosing amalgam, such as titanium-mercury, a precise mass of which can be built into the CFL during assembly. Once the CFL is sealed, elemental mercury is permanently freed from this alloy using radio frequency heating. (Alessio Corazza, Giorgi, & Massaro, 2008) The other is a getter alloy, such as Zr-Al, which can absorb impurities in the inert buffer gas such as water, hydrogen, carbon monoxide, nitrogen, carbon dioxide, and methane, which can affect lamp performance. (A. Corazza, Giorgi, & Massaro, 2011)

CFLs that use amalgams to regulate mercury vapor pressure during operation may or may not be labeled as amalgam-based CFLs. If only dosing and/ or getter amalgams are used, the CFL is not considered to be amalgam-based.

When a CFL with liquid (elemental) mercury has been in the off state and has cooled down to room temperature, the mercury forms many small droplets on the inner bulb walls. Upon being turned on, the heat from the electrical arc evaporates some of the mercury until the equilibrium mercury vapor pressure is reached for that operating temperature. During operation, most of the mercury remains as a liquid at the lamp's "cold spot" or "minimum bulb wall temperature location." This excess mercury is provided in anticipation of some mercury being entrapped by the bulb wall and phosphors during the life of the lamp. After the lamp is turned off, the temperature decreases so the vapor pressure decreases and much of the mercury that had been in vapor form again condenses on the inner bulb walls. (H. Trevino, 2012)

H. Trevino (2012) states "For amalgam lamps,when the lamp is off all mercury is in solid state and it's contained in the main and auxiliary amalgams. When the lamp is started, the mercury is freed from the auxiliary amalgam flag by heat from the electrode. Some mercury is also released from the main amalgam. When the main amalgam warms up (usually after a few minutes of lamp operation), the main amalgam absorbs mercury, with the amount corresponding to the lamp's temperature. During stable operation most of the mercury will be contained in the main amalgam and a little portion will be in vapor form in the discharge tube." Serres and Taelman (1993) found that after the CFL is turned off, the auxiliary amalgam absorbs mercury. In the first eight to 16 hours after being turned off, the mercury content of the auxiliary amalgam rises to 20%, but then continues to rise for the next 100 hours until equilibrium is reached. Ito (2012) states that during this period of mercury absorption in the auxiliary amalgam, liquid mercury droplets condense on the inner bulb wall. This implies that for CFLs used on a daily basis, most of the mercury that was in the vapor phase will be in a liquid phase rather than trapped in an amalgam when the lamp is off (but this is a fraction of the mercury in the lamp).

The Amount of Mercury in CFLs

According to NRCan, CFLs contain an average of 4 mg of mercury. (NRCan 2011. Please see the web page http://oee.nrcan.gc.ca/equipment/manufacturers/15286)

In the United States, the National Electrical Manufacturers Association (NEMA) set a voluntary maximum amount of mercury in CFLs less than 25 W at 4 mg. (NEMA, 2011) (This replaces an older, slightly higher voluntary limit on the amount of mercury in CFLs.) In order to allow for manufacturing variation, this represents a maximum average amount across all the lamps of a particular model, not a limit for each lamp. Fourteen manufacturers, including major manufacturers, have committed to abide by this limit. (NEMA 2010) NEMA's declaration of conformance states that "All products sold by a manufacturer must be covered in order to be listed on the NEMA website."

The Northeast Waste Management Officials' Association found that of all CFLs sold by NEMA member companies in 2004, 66% had 0 to 5 mg of mercury, 30% had 5 to 10 mg of mercury, and 4% had 10 to 50 mg of mercury. (Northeast Waste Management Officials' Association (NEWMOA), 2008) Although typical CFLs currently on the market have less mercury, it is likely that some of the lamps sold in 2004 are still in use.

A study conducted in 2009 in Brazil found that six out of 15 CFL models tested contained more than 5 mg of mercury, the limit set by the European Union. One model contained 27 mg of mercury. (dos Santos et al., 2010)

A recent report by ICF Marbek (2012) polled manufacturers regarding sales of CFL lamps to determine the percentage of lamps using amalgam vs. liquid mercury. The results showed that 83% of CFL lamps sold in 2011 are amalgam-based, while the remaining 17% are elemental-mercury based. (The authors of the study confirmed that "amalgam-based" refers to CFLs that use amalgam to regulate mercury vapor pressure rather than to dose the lamps.) The most commonly sold products containing amalgam were uncovered spiral CFLs. ICF Marbek (2012) also stated that a 2008 mercury content survey by the Equipment Manufacturers Association of Canada (EEMAC) showed that the average mercury content for all CFL lamps was 3.7 mg. According to Environment Canada, average mercury content in CFL lamps was 7.6 mg until 2011, decreasing to 3.5 mg from 2012 and forward (ICF Marbek , 2012).

Health Effects Of Mercury

Mercury is a naturally occurring element that is found in water, soil and air. There are three chemical forms of mercury - elemental mercury (Hg0), methylmercury (a form of organic mercury) and mercury compounds that can be organic or inorganic (such as mercuric chloride). (United States Environmental Protection Agency, 1997) Health effects from mercury are dependent on the chemical form of mercury, dose, age of exposed person, duration of exposure, route of exposure, and the health of the exposed person. (United States Environmental Protection Agency, 2010)

The primary exposure to mercury for people living in the US (and presumably Canada) is via organic methylmercury found in fish and shellfish. (Bernhoft, 2012) Methylated mercury in the aquatic environment is found in fish and seafood with higher accumulation found higher up the food chain. Chronic exposure to mercury vapor can also occur from occupational exposure and through outgassing from dental amalgams. (Bernhoft, 2012) Sandborgh-Englund found that the amount of elemental mercury inhalation dose from amalgam fillings (for the typical amount of fillings per mouth) was 5,000-9,000 ng/day. (Sandborgh-englund et al., 1998)

Toxicokinetics of elemental mercury

Toxicokinetic functions describe how a toxin is absorbed, distributed, metabolized and excreted. The toxicokinetics of elemental mercury are as follows. Most elemental mercury (70-85%) is ingested through inhalation, in the form of mercury vapor. (Bernhoft, 2012; Bose-O'Reilly, McCarty, Steckling, & Lettmeier, 2010; United States Environmental Protection Agency, 1997) In contrast, 7 - 10% of ingested elemental mercury is absorbed through the gastrointestinal tract and only 1% of elemental mercury is absorbed via dermal contact. (United States Environmental Protection Agency, 1997b)

Mercury vapor crosses both the blood-brain barrier and placental barrier. Chronic exposure to high levels of mercury vapor results in neurological dysfunction. (United States Environmental Protection Agency, 1997) Excretion of elemental mercury occurs via urine, feces, exhaled air, sweat and saliva. Retention of elemental mercury in the human body depends on the metabolic pathways. In one study, it was found that the median retention rate of a single dose of mercury vapor was 70% after 30 days. (Sandborgh-englund et al., 1998) US EPA indicates the half-life for excretion of elemental mercury is about 60 days. (United States Environmental Protection Agency, 1997)

Health effects from elemental mercury exposure

Adverse effects from acute or chronic mercury exposure will occur for all humans. However, children are at particularly high risk because of developmental vulnerabilities, lower body weight, childhood behaviors (such as playing with soil and placing their hands in their mouths) and because of their attraction to elemental mercury's physical appearance. (Bose-O'Reilly, McCarty, Steckling, & Lettmeier, 2010) Breathing rates per unit of body weight are higher in infants and young children (5 years old and younger) than in adults. (Miller et al., 2002) Mercury vapor is also heavier than air, and children are more susceptible to mercury poisoning than adults because of their short stature. Miller notes one CDC case study where children were affected with acute mercury poisoning in the household but adults in the same household were not affected. Children also have smaller airways that tend to have increased particle deposition compared to adults. Particle deposition model for lungs is predicted to have inverse relationship to body size. (Miller et al., 2002)

Fetuses and infants are also especially vulnerable to mercury exposure. For these subpopulations, mercury exposure can cause permanent damage to the nervous system. (Bose-O'Reilly, McCarty, Steckling, & Lettmeier, 2010)

Acute exposure to large amounts of mercury vapor leads to respiratory distress, which can be fatal. Cessation of exposure may lead to symptoms disappearing but persistent neurological symptoms are common. Low level chronic exposure leads to various non-neurological symptoms including fatigue, weight loss, weakness and gastrointestinal disturbances. (United States Environmental Protection Agency, 1997)

Another symptom of elemental mercury exposure is acrodynia - meaning "painful extremities". The symptoms of acrodynia are red, puffy hands and feet with peeling skin. Other common comorbid symptoms with acrodynia include anorexia, insomnia, irritability, profuse sweating and resulting malaria-like rashes, as well as photophobia. (Tunnessen, McMahon, & Baser, 1987)

Comparing exposure from methylmercury in fish to elemental mercury vapor

Ninety-five percent of ingested methylmercury is rapidly and efficiently absorbed through the gastrointestinal tract, compared to only 7-10% for elemental mercury. (United States Environmental Protection Agency, 1997) Both methylmercury and elemental mercury cross both the blood-brain barrier and placental barrier. (United States Environmental Protection Agency, 1997) About 80% of methylmercury vapor is absorbed via inhalation, which is similar to elemental mercury (70-80%). (Bose-O'Reilly, McCarty, Steckling, & Lettmeier, 2010) Unlike elemental mercury, methylmercury is efficiently absorbed through the skin. Excretion of methylmercury occurs via urine, feces and breast milk, but not sweat, saliva, or exhaled air as with elemental mercury. US EPA indicates the chronic half-life for excretion of methylmercury is about 75 days, compared to about 60 days for elemental mercury. (United States Environmental Protection Agency, 1997) (This is based on the assumption that mercury exists in a steady state in the body; in other words that these people are frequent fish eaters. For one fishmeal containing methylmercury, the acute half-life is 48 hours.) The toxicity and central nervous system (CNS) effects are different. Even for the same input, there are different routes for these types of mercury through the body, different symptoms and different end points. In addition to these differences in physiology, different effects on the human body are used to set the exposure limits for each. For methylmercury, exposure limits are based on neurological effects in offspring of pregnant women, while for elemental mercury limits are based on neurological effects in the subject him or herself. Because of all of these differences between methyl- and elemental mercury, it is inaccurate to directly compare methylmercury exposure to elemental mercury exposure.

Exposure Guideline Levels

Exposure guidelines have been developed by various governmental agencies, researchers and organizations for both acute and chronic mercury exposure. For many of these guidelines, the reference exposure represents an estimate of the exposure that will likely not appreciably increase risk of deleterious effects over a lifetime. It is often based on a lowest observed adverse effect level (LOAEL) exposure limit that is adjusted to a reference exposure limit via an uncertainty factor (UF). There is an accepted rubric for determining the UF factor, but these factors are typically a function not only of the data sets themselves but also a function of the data interpretation and perspective. In addition, the general population guidelines are for continuous exposure for a long time and do not assume a healthy population. (US EPA, REL CA OEHHA, MRL). The exposure guideline levels themselves therefore have uncertainty; a toxicology expert from NYS DOH suggested that although the exposure guidelines show a high precision number, those guidelines that are within one order-of-magnitude of each other can be assumed to be the same. (Fritz 2012)

Deciding which guideline to use, acute or chronic, depends on how the spill is handled, and on the scenario. According to a toxicology expert with the NYS DOH, if a spill is not cleaned up, this may result in a chronic low level exposure. With warm weather and a very small space, this may result in higher absolute values of mercury vapor. In addition, certain sub-populations such as infants and children are at higher risk if they are in the space during "high" levels of mercury exposure. Exposure patterns may be very important as well; spikes in mercury levels may be more important than chronic levels. (Fritz 2012)

Table 1 and Table 2 provide a list of the exposure guidelines found in the literature review.

Table 1: North American and European Union acute exposure guideline levels for mercury vapor. See definitions of abbreviations below. Note that no acute exposure limits set by Canada were identified.

Name of exposure limit	Agency setting the exposure limit	Geographical membership of agency setting the exposure limit	Exposure vapor concentration (ng/m^3) limit for these exposure durations:				
			10 min	30 min	1 hour	4 hour	8 hour
AEGL-1	National Advisory Committee for Acute Exposure Guideline Levels	Primarily US with some foreign governmental members (Canada, Sweden, The Netherlands)	not recommended				
AEGL-2	National Advisory Committee for Acute Exposure Guideline Levels	Primarily US with some foreign governmental members (Canada, Sweden, The Netherlands)	3,100,000	2,100,000	1,700,000	670,000	330,000

AEGL-3	National Advisory Committee for Acute Exposure Guideline Levels	Primarily US with some foreign governmental members (Canada, Sweden, The Netherlands)	16,000,000	11,000,000	8,900,000	2,200,000	2,200,000
ERPG-1 (AIHA)	American Industrial Hygiene Association	US, allows international affiliate members			not recommended		
ERPG-2 (AIHA)	American Industrial Hygiene Association	US, allows international affiliate members			2,000,000		
ERPG-3 (AIHA)	American Industrial Hygiene Association	US, allows international affiliate members			4,100,000		
SMAC (NRC)	National Research Council	US			80,000		
PEL ceiling (OSHA)	Occupational Safety and Health Administration	US	1,000,000				
IDLH (NIOSH)	National Institute of Occupational Safety and Health	US		10,000,000			
STEL (CFR 1989)	Code of Federal Regulations	US	100,000				
REL (CA OEHHA)	California Office of Environmental Health Hazard	California			600		60

Maine has set their Maine Ambient Air Guideline (MAAG) to 300 ng/m^3 for acute exposure by matching the US EPA’s RfC chronic exposure level. However, it is not clear to the LRC for what exposure duration the MAAG applies to.

The LRC was not able to identify an acute exposure level for elemental mercury set by the Canadian government.

Table 2: North American and European Union chronic exposure guideline levels for mercury vapor. See definitions of abbreviations below.

Name of exposure limit	Agency setting the exposure limit	Geographical membership of agency setting the exposure limit	Uncertainty Factor	Exposure vapor concentration (ng/m^3) limit				
				Measured LOAEL	Adj. LOAEL (continuous exposure)	Measured NOAEL	RfC	RfD
RfC (EPA)	Environmental Protection Agenc	US	30	25,000	9,000	none	300	not given
WHO air quality guideline (Annual)	World Health Organization	United Nations					1,000	
WHO IPCS Guideline (long term)	World Health Organization	United Nations			4,800		200	
Indoor air guidelines (RWI)	German Federal Environment Agency	Germany					35	
Indoor air guidelines (RWII)	German Federal Environment Agency	Germany					350	
REL-TWA (NIOSH)	National Institute of Occupational Safety and Health	US					50,000	
TLV-TWA (ACGIH)	American Conference of Governmental Industrial Hygienists	US					25,000	
MAK	Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area	Germany					100,000	
MAC	Ministry of Social Affairs and Employment	The Netherlands		500,000			50,000	

PEL 8 hour TWA (OSHA)	Occupational Safety and Health Administration	US					100,000	
REL (CA OEHHA)	California Office of Environmental Health Hazard	California	300	25,000	9,000	none	30	160
MRL (ATSDR)	Agency for Toxic Substances and Disease Registry	US		26,000			200	300
Provisional Mercury Vapor (tolerable concentration) (Health Canada)	Health Canada	Canada	100		6,000		600	
Proposed RfC for adults (Beate 2010)	N/A	any	50	3,500			70	

Below are explanations from the US EPA and/ or NAC (National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances, 2010; United States Environmental Protection Agency, 2011) of the abbreviations used in Table 1 and Table 2.

RfC - estimate of the daily human inhalation exposure that will likely not appreciably increase risk of deleterious effects over a lifetime

RfD - estimate of the daily human oral exposure that will likely not appreciably increase risk of deleterious effects over a lifetime (reference dose)

REL - recommended exposure limit

PEL - permissible exposure limit

TLV - threshold limit value

NOAEL - no observed adverse effect level, defined as the highest exposure level at which there are no biologically significant increases in the frequency or severity of adverse effect between the exposed population and its appropriate control; some effects may be produced at this level, but they are not considered adverse or precursors of adverse effects

LOAEL - low observed adverse effect level, defined as the lowest exposure level at which there are biologically significant increases in frequency or severity of adverse effects between the exposed population and its appropriate control group

RW I - Concentration of a substance in indoor air for which, when considered individually, there is no evidence at present that even lifelong exposure is expected to have any adverse health impacts.

RW II: Effect-related value based on current toxicological and epidemiological knowledge of a substance's effect threshold, which takes uncertainty factors into account.

WHO Guideline Values - Air: 1 µg/m3 (annual average). WHO estimates a tolerable concentration of 0.2 µg/m3 for long-term inhalation exposure to elemental mercury vapor (based on LOAEL using continuous exposure and based on average exposure to 20 µg/m^3 elemental mercury, and a tolerable intake of total mercury of 2 µg/kg body weight per day.

Provisional Mercury Vapor (tolerable concentration) (Health Canada) - maximum concentration level given under Annex C Health Canada Guidelines. Richardson et al 2009 is cited as source. (Richardson et al., 2009)

MRL ASTDR (Agency for Toxic Substances and Disease Registry) - Minimal Risk Level (MRL)

AEGLs represent threshold exposure limits for the general public and are applicable to emergency exposure periods ranging from 10 minutes to 8 hours. Three levels are provided: AEGL-1, AEGL-2 and AEGL-3 These limits are developed for each of five exposure periods (10 and 30 minutes, 1 hour, 4 hours, and 8 hours) and are distinguished by varying degrees of severity of toxic effects. AEGL-1 is defined as the airborne concentration level of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic, non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure. Because there are no sensory or irritant warning characteristics for these low concentrations, AEGL-1 values are not recommended. AEGL-2 is defined as the airborne concentration level of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. AEGL-2 values are based on NOAEL for developmental effects in pregnant rats, based on a 2 hour/day, 10 day exposure to 4 mg/m^3 of mercury vapor. AGL-3 is the airborne concentration level of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death. AEGL-3 values are based on highest 1-hour non-lethal exposure of rats: 26.7 mg/m^3

ERPG - Emergency response planning guidelines, American Industrial Hygiene Association. ERPG-1 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to one hour without experiencing other than mild, transient adverse health effects or without perceiving a clearly defined objectionable odor. ERPG-2 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action. ERPG-3 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects.

SMAC (Spacecraft Maximum Allowable Concentration, National Research Council). SMACs are intended to provide guidance on chemical exposures during normal operations of spacecraft as well as emergency situations. The one-hour SMAC is a concentration of airborne substance that will not compromise the performance of specific tasks by astronauts during emergency conditions or cause serious or permanent toxic effects. Such exposures may cause reversible effects such as skin or eye irritation, but they are not expected to impair judgment or interfere with proper responses to emergencies.

OSHA PEL-TWA (Occupational Safety and Health Administration, Permissible Exposure Limits - Time Weighted Average). OSHA PEL-TWA is defined analogous to the ACGIH-TLV-TWA, but is for exposures of no more than 10 hours/day, 40 hours/week.

OSHA PEL ceiling value - under OSHA Guidelines for mercury vapor. A worker's exposure to mercury vapor shall at no time exceed this ceiling level.

IDLH (Immediately Dangerous to Life and Health, National Institute of Occupational Safety and Health). IDLH represents the maximum concentration from which one could escape within 30 minutes without any escape-impairing symptoms, or any irreversible health effects.

NIOSH REL-TWA (National Institute of Occupational Safety and Health, Recommended Exposure Limits – Time Weighted Average) is defined analogous to the ACGIH-TLV-TWA. NIOSH also assigns a Skin notation, which indicates that cutaneous routes of exposure including membranes and eyes contribute to overall exposure.

ACGIH TLV-TWA (American Conference of Governmental Industrial Hygienists, Threshold Limit Value - TimeWeighted Average) The time-weighted average concentration for a normal 8-hour workday and a 40-hour work week, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.

MAK (Maximale Arbeitsplatzkonzentration [Maximum Workplace Concentration]) is defined analogous to the ACGIH-TLV-TWA. For mercury, category II (8) indicates an excursion factor of 2, 8 times during the shift.

MAC (Maximaal Aanvaarde Concentratie [Maximal Accepted Concentration]) (SDU Uitgevers [under the auspices of the Ministry of Social Affairs and Employment], The Hague, The Netherlands 2000) is defined analogous to the ACGIH-TLV-TWA. The 15-minute peak is 0.5 mg/m^3

REL California Office of Environmental Health Hazard (CA OEHHA) REL types: A = acute, 8 = 8-hour, C = chronic. Exposure averaging time for acute RELs is 1 hour. For 8-hour RELs, the exposure averaging time is 8 hours, which may be repeated. Chronic RELs are designed to address continuous exposures for up to a lifetime: the exposure metric used is the annual average exposure.

STEL (CFR 1989) Short term exposure limit (15 minutes) Code of Federal Regulations (CFR)

Amount of Mercury Released from Broken CFLs

As discussed above, breathing in mercury vapor is by far the greatest risk to human health from a broken CFL, rather than, say, touching mercury during clean up. The LRC identified two studies that measured mercury vapor concentrations from broken CFLs under realistic residential or office conditions. The first was led by Deb Stahler at the Maine (United States) Department of Environmental Protection. (Stahler, Ladner, & Jackson, 2008) The second was led by Dr. Tunga Salthammer of the Fraunhofer-Institute for Wood Research, Wilhelm-Klauditz-Institut WKI in Braunschweig, Germany. (Salthammer, Uhde, Omelan, Lüdecke, & Moriske, 2011). A third relevant study was identified, but an English translation of this German article could not be obtained in time for this report. (Fromme et al., 2011) However, based on that study's abstract and a summary in the Salthammer paper, the results were similar to those of the Salthammer study. The LRC reviewed other studies, such as the URS study for the United States Post Office, but found that they were not as directly relevant to the residential or office environment. (Vidich & Grover, 2005)

The most relevant results of the two primary papers reviewed are presented in "Appendix B: Results of Stahler and Salthammer Papers," below. Salthammer specified that the amount of mercury present in the lamps used in that study ranged between 1.5 mg and 5 mg. Stahler did not specify the amount of mercury in the CFLs used in that study, but were presumably within the range described in the section "The Amount of Mercury in CFLs," above. The Stahler study provides results of multiple trials of the same test scenario, and the results indicate that mercury concentrations often vary by two to five times between trials. This is likely to occur because of variability in the breakage of the glass bulb and location of the mercury inside the bulb. It would not be surprising if the Salthammer experiments found similar variability. (This is hinted at when Salthammer provides counter-intuitive results, such as in one case when breaking a cold CFL produced a higher mercury concentration than breaking a recently operated one.) This variability should be kept in mind as the results discussed in this report are considered.

The recommended procedure when a CFL breaks is to open a window and then leave the room for 15 minutes. (Health Canada, 2011) If this procedure is followed within a minute of the CFL breaking and the CFL breaks at a distance of 1.5 m from the occupant's face (such as an adult dropping a CFL on the floor), then the first time that the person will be exposed to elevated levels of mercury vapor is when they return after 15 minutes to clean up the broken CFL. Salthammer found that after ventilating the room, mercury concentration levels declined to 12 ng/m^3. This is less than all acute and chronic exposure limits shown in Table 1 and Table 2. Stahler too found reduced exposure levels after ventilation, but reported them only as being below 300 ng/m^3, the relevant exposure limit in Maine (MAAG), where the study was carried out. These results show that a person can return to a ventilated room to clean up the broken CFL without concern about mercury exposure levels.

After cleaning up a broken CFL using recommended procedures, Stahler and Salthammer found that the mercury concentrations are reduced below all chronic exposure guidelines. Salthammer found mercury concentrations of 6 ng/m^3 after 21 hours (on a laminate floor) and 19 ng/m^3 after 3 hours on a carpet. Both of these concentrations are below all chronic exposure limits shown in Table 2. For example, the US EPA's RfC is 300 ng/m^3 and Health Canada's provisional tolerable exposure level is 600 ng/m^3. Stahler reported that in 10 of 11 relevant cases, the mercury concentration was below 50 ng/m^3, the chronic exposure guideline in Maine, where the study was conducted. In the 11th case, concentrations were found to still briefly spike over 50 ng/m^3 but below 300 ng/m^3 when the last measurement was taken 2.8 hours after cleaning up the CFL.

Based on the reviewed studies, a person following recommended procedures for cleaning up a broken CFL will not be exposed to enough mercury vapor concentration to violate any identified acute or chronic exposure limits.

CFL Breakage Scenarios of Special Concern

Occupant is unaware of CFL breakage or recommended clean up procedures

It is possible that a CFL could break without an occupant being aware of it or that they should ventilate the room for 15 minutes before returning.

Stahler et al found that the peak concentration in a room with the window closed was about 35,000 ng/m^3. This is lower than the maximum peak concentration found when the window was open, 65,000 ng/m^3, showing that variability between CFLs and between experimental trials has more effect than room ventilation. In the test scenarios in the Salthammer and Stahler studies when the window was opened, mercury concentrations fell below 300 ng/m^3 in less than 10 minutes. The 10 minute average mercury concentration the occupant will be exposed to would be lower than the peak value, but even if it were as high as the peak value, it would still fall below the 10 minute acute exposure limits shown in Table 1.

"Appendix B: Results of Stahler and Salthammer Papers" provides the maximum one-hour average mercury concentrations from the Stahler study for the 13 non-vacuum scenarios. Of these 13 values, eight fall below all of the one-hour average exposure shown in Table 1. The remaining five fall below all of the limits except for the California REL (CA OEHHA) value of 600 ng/m^3. California bases its limit on the same experimental data as the other agencies and is setting its limit for the same general population, including pregnant women and infants, as other agencies. The difference is that California applied a much larger uncertainty factor to the data than other agencies (CA OEHHA 2008).

Even in the case when a CFL is not cleaned up, the mercury on the flooring will evaporate and be removed through air exchanges that occur in all buildings. Michael Aucott of the New Jersey Department of Environmental Protection measured the long-term release of elemental mercury from a broken fluorescent lamp and found that the amount of mercury released decreases logarithmically over time, as shown in Figure 1. (Aucott, McLinden, & Winka, 2004) Aucott calculated that over two weeks, a quarter to a half of the total mercury in the lamp was released. Using Aucott's mercury release rate curve fit and assuming a 40 m^3 room, a CFL with 4.55 mg of mercury, and one air change per hour, it would take about 9.3 hours until the mercury concentration falls below 300 ng/m^3, a concentration typical of chronic exposure limits, and 8 days to fall below 35 ng/m^3, the lowest chronic exposure limit shown in Table 2. It would take one year and two months for the mercury from the broken CFL to match the natural background concentration of about 2 ng/m^3. In other words, after a year the concentration would be twice the exposure level that would be present without the CFL breaking, but still an order of magnitude lower than the lowest chronic mercury exposure levels (set by California and Germany). Note that chronic exposure limits anticipate a possible lifetime of exposure. If an amalgam CFL were broken, then presumably the mercury would evaporate more slowly, but the concentration in the air would be lower as well. The exact rates and concentrations would depend on the amalgam used.

Also, assuming an excretion rate discussed in the section "Toxicokinetics of elemental mercury" above, about 90% of elemental mercury would be excreted in half a year. In other words, even if a person remained in a room with a broken CFL, that person's body would remove almost all of the absorbed mercury within half a year.

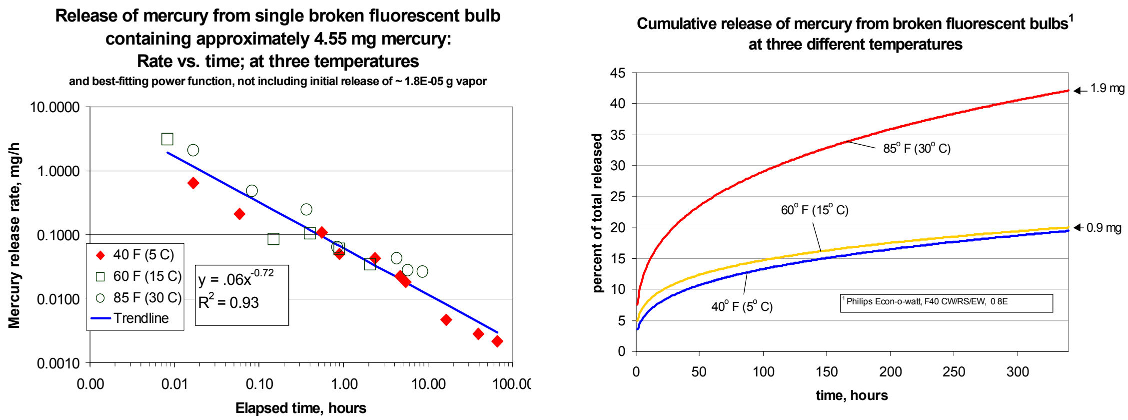

Figure 1: Long-term mercury release from a broken fluorescent lamp. (Aucott et al., 2004)

Occupant is holding CFL at time of breakage

Stahler (2008) provides measurements of mercury vapor concentrations at 0.3 m and 1.5 m above the ground. The experimental setup is shown in a photograph in that report, and the measurements are made almost vertically above the broken CFL (perhaps offset by 15 cm horizontally). Therefore, the 0.3 m measurement values could approximate the exposure levels of someone holding a CFL in his or her hand at the time of breakage. Stahler provides plots of mercury vapor concentrations at the 0.3 m and 1.5 m measurement heights over time. These plots show that the peak mercury vapor concentrations are reached within 10 seconds at 0.3 m but only after approximately one minute at the 1.5 m height.

For this reason, if an adult occupant drops a CFL and then leaves the room immediately (or perhaps pausing for a few seconds to open a window), it is likely that the occupant will not be exposed to elevated mercury concentrations until he or she returns to clean up the CFL. However if someone is close to the CFL at time of breakage, such as an adult holding the CFL or a CFL breaking on the ground near a small child, then that person would be exposed to peak mercury concentrations within 10 seconds. In that case, the situation would be analogous to the occupant not leaving the room, as described in the section "Occupant is unaware of CFL breakage or recommended clean up procedures" above. The peak concentration values given in that section are for the 0.3 m measurement height, so they are representative of this situation.

Pregnant woman or infant in room with broken CFL

The chronic and acute exposure limits shown in Table 1 and Table 2 are for the general population and take into account data related to pregnant women, infants, and young children. However, the Stahler report describes uncertainties in setting exposure limits for these vulnerable populations: (Stahler, Ladner, & Jackson, 2008)

> It is well established that the developing organism may be much more sensitive than the adult to neurotoxic agents…. The processes unique to the developing brain do not end at birth. Therefore, the brains of infants and young children are also at increased vulnerability to damage from chemical exposure. Infants and children are also at increased risk because at any given air concentration, the internal dose of mercury would be greater than that of the adult as a consequence of increased ventilation rate (breathing more air per unit of time) as well as

> less efficient ability to excrete mercury from the body. In this regard, it is also important to understand that mercury is transported directly into the brain following inhalation, as well as being absorbed into the blood from the lung. An important issue for which there are no data is the relative importance of a short spike in exposure versus a longer-term lower exposure in producing toxicity. The U.S. EPA considers that a single exposure may be sufficient to produce effects in a developing organism because of the recognition of potential critical windows of vulnerability. This implies that any exposure over an accepted toxicity value is potentially cause for concern, since a single exposure may produce a perturbation in a single or multiple processes in discrete brain areas, depending on the developmental stage of the exposure. Any such perturbations may have "downstream" consequences: if A doesn't happen, then B and C cannot happen in a normal manner. Repeated exposures would presumably increase the probability of untoward consequences. In addition, the relative risk of various exposure metrics is unknown: whether the greatest risk is posed by short-term higher level peak exposures or by the total area under the curve including higher and lower exposures. Because of the potential unique vulnerability of the brain of the fetus and infant, and the lack of information concerning the risk posed to vulnerable populations by various exposure scenarios, the most health-protective strategy is to consider that any exposure greater than the [Maine Ambient Air Guideline] (MAAG) of 300 ng/m^3 may potentially result in adverse health consequences.

If the Canadian government were to recommend that households with pregnant women and young children avoid the use of CFLs due to these uncertainties, then alternative light sources such as halogen and LED, which do not contain mercury, could be suggested.

Vacuum used in clean up

Stahler et al conducted extensive testing of vacuum clean up of broken CFLs and found that: (Stahler, Ladner, & Jackson, 2008)

> The study does not support recommending vacuuming as a clean up option. Vacuuming is problematic because it tends to mix mercury concentrations in the room, promoting higher concentrations in the five foot breathing zone. In addition, the vacuum may become contaminated. Although using a wet wipe on some vacuum surfaces helped to lower residual mercury, expensive testing equipment was needed to evaluate clean up effectiveness. Also some parts of the vacuum, such as the inside of the hose, are not as easy to wipe. The vacuum bag, when there is one, would need to be treated as universal waste if contaminated with mercury.

This study showed that vacuums should not be used to clean broken CFLs.

Breaking multiple CFLs

Mercury vapor concentrations in air are proportional to the amount of mercury released by broken lamps. Therefore, it is possible that multiple broken CFLs would produce dangerous amounts of mercury vapor in cases where a single CFL would not. The United States Post Office found that 4 broken CFLs could exceed the NIOSH ceiling value of 0.1 mg/m^3. (Vidich & Grover, 2005) This could be a concern for shipping and storage applications and households that store a number of CFLs.

CFL is, or was recently, operating at time of breakage

The Salthammer and Stahler studies appear to provide conflicting information about the effect of the CFL being on immediately before being broken. Stahler's test scenario "SD" involved breaking a CFL that had been on for one hour prior to breaking it, but the resulting mercury concentrations are no higher than many of the cold-CFL scenarios. On the other hand, Salthammer found when breaking CFLs that had been operating for one hour, the mercury concentrations were 2.5 to 52 times higher for the hot CFLs.

CFL Features That May Reduce Mercury Release

Two available CFL features have the potential to reduce the likelihood that a CFL will release mercury if it is dropped or struck:

1) Shatter-resistant coatings. Some CFLs are available with a clear silicone coating applied to the spiral glass bulb.
2) Covered CFLs. Some CFLs have an outer glass or polymer covering in the shape of a globe or A-shaped lamp.

Also, amalgam CFLs have the potential to produce lower mercury vapor concentrations when broken compared with elemental mercury CFLs.

Silicone Shatter-Resistant Coatings

A study conducted by Ecos Consulting (2009) of two CFL models with shatter-resistant silicone coatings found that although in 74% of the samples the spiral glass bulb cracked, the silicone appeared to contain the broken glass and "visual inspection did not reveal any breakage in the silicone covering." Also, Salthammer found that a CFL with a shatter-resistant coating released 5 times less mercury vapor than a comparable non-shatter-resistant CFL when they were broken in a cold (off) state (33 vs. 150 ng/m^3) and 600 times less mercury vapor in the hot state (13 vs. 7820 ng/m^3). (Salthammer, Uhde, Omelan, Lüdecke, & Moriske, 2011) However, Salthammer used different methods to break the two types of CFLs. For the uncoated CFL, a steel bar "destroyed" the CFL. For the shatter-proof CFL, the lamp was "dropped from a height of 1.9 m deliberately so that it fell on its cap." Presumably, the bulb of the non-coated CFL was broken more thoroughly than if it had been dropped, so this could be responsible for at least some of the difference. (Salthammer, Uhde, Omelan, Lüdecke, & Moriske, 2011) Also, an informal test previously conducted by the LRC found that when a CFL with a silicone coating was dropped on a wood floor, the glass bulb completely separated from lamp base with the ballast, providing an opportunity for mercury vapor to escape to the environment.

Covered CFLs

A study conducted by Ecos Consulting (2009) of seven models of covered CFLs found that "The glass casing significantly reduces the chance of CFL tube breakage in the event a bulb is dropped on carpet. The glass casing takes the brunt of the impact, which helps to protect the tubing…. There is less than a 3% chance that the CFL tubing encased in a glass covering will break when dropped on unpadded carpet from a height of 7 feet. Even if the inner CFL tubing breaks, the outer glass covering may survive intact, likely minimizing mercury release. There is an 8% chance that a glass-encased CFL bulb will be damaged when dropped, but the CFL tube does not break (e.g., base becomes loose, exterior casing cracks or breaks, but no mercury is likely to be released)." As shown in Figure 1, lamps with the glass casing compared favorably (3% broken) to those with a silicon covering (74% broken) and with no special coating protection (77%). (Ecos Consulting, 2009)

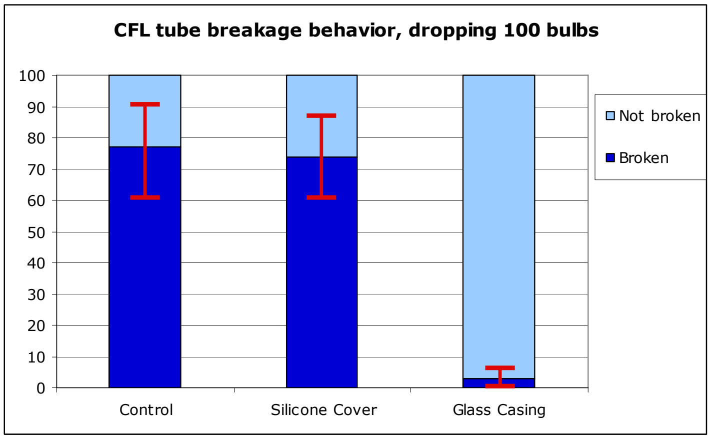

Figure 2: CFL Tube Breakage Behavior with Error Bars. (Ecos Consulting, 2009)

The Stahler study included both covered and bare spiral CFLs. No correlation with mercury vapor concentrations was apparent in the data, as would be expected because all of the CFLs were "thoroughly" broken with a hammer.

Amalgam CFLs

Salthammer found in a test chamber that broken amalgam CFLs produced 22 to 28 times lower mercury vapor concentrations than liquid mercury CFLs when the lamps had been operated for one hour prior to breaking, and 6 to 12 times lower mercury vapor concentrations when the lamps had been cold. (Salthammer, Uhde, Omelan, Lüdecke, & Moriske, 2011) Stahler found amalgam reduced the mercury vapor concentration by 25 times for cold CFLs. (Stahler, Ladner, & Jackson, 2008)

Results of Photometric Testing

As discussed above, covered and shatter-resistant CFLs demonstrate reduced risk of mercury exposure. One downside to using these lamps is a small decrease in efficacy because the outer covering absorbs some light. In other words, more power is needed to produce the same amount of light from a bare, uncoated CFL.

The LRC conducted photometric testing of three different shatter-resistant coating types for the US EPA and "found that the type of coating plays a role in both the initial light output and the lumen maintenance values. The additional effect of light output reduction due to coating depends on different coating types and different life stages (100-hour, 1000-hour, and 40% life), ranging from 1% to 10%. In some cases the coating reduces the light output more over time, and in some other cases the coating reduces the light output less over time." (O'Rourke, Zhou, & Figueiro, 2009)

For the current study, the LRC tested 10 CFLs provided by NRCan. Four of them were covered A-lamp shaped CFLs and the other 6 were bare spiral CFLs. They all had a power draw in the range of 12 to 15 W and a luminous flux in the range of about 790 to 950 lm.
The bare spiral CFLs had an average efficacy of 63.9 lm/W with a
standard deviation of 2.5. The covered CFLs had an average efficacy of 60.4 lm/W, with a standard deviation of 2.9. The average covered efficacy is 5.5% lower than the average bare-spiral lamp efficacy.

A consumer using a CFL instead of an incandescent lamp will reduce energy usage about 65%. If the consumer were to "give back" about 6% of this energy savings to reduce the risk of mercury exposure, this loss of savings is relatively minor in comparison. It might even increase the use of energy efficient lighting by increasing the acceptance of CFL technology.

Some consumers are concerned about the run-up time of CFLs. Amalgam CFLs can have longer run-up times than elemental mercury CFLs. For example, The Energy Star Program Requirements for Compact Fluorescent Lamps (CFLs) version 4.2 allow a run-up time of less than 1.0 minute for bare non-amalgam CFLs but allow up to 3.0 minutes for bare amalgam CFLs.

Cleaning Procedures For Broken CFLs

The LRC reviewed Health Canada's CFL clean up procedures provided at http://www.hc-sc.gc.ca/hl-vs/iyh-vsv/prod/cfl-afc-eng.php. These cleaning procedures are up to date and reflect the findings of the recent studies discussed in this report. The most important part of the cleaning procedure is to leave the room quickly, ideally opening up an exterior window on the way out of the room, and letting the room ventilate before returning. If this procedure is followed, then the occupants should not be exposed to mercury vapor concentrations that violate any exposure limits identified by the LRC.

The Stahler paper makes some suggestions that the Canadian government might consider passing on to its constituents: (Stahler, Ladner, & Jackson, 2008)

- Suggesting that homeowners consider removal of carpeting sections where breakage has occurred as a precaution in some situations, particularly in homes with infants, small children or pregnant women. Repeated vacuuming can result in elevated mercury levels close to the carpet at a height where children are exposed. Vaccuming can also contaminate vacuum and internal components with traces of mercury are difficult, if not impossible, to clean. ;
- Suggesting that homeowners consider not utilizing fluorescent lamps in situations where they could easily be broken, in bedrooms used by infants, small children or pregnant women, or over carpets in rooms frequented by infants, small children or pregnant women; and

- Avoiding the storage of too many used/spent lamps before recycling that could increase the chances of breakage.

Research is being done on nanotechnology products (e.g., nano selenium fabric) that may aid in the absorption of elemental mercury from broken CFLs. (Johnson, Manchester, Sarin, Gao, Kulaots, & Hurt, 2008) Canada may wish to monitor the development of such products.

Conclusions and Recommendations

The LRC sought to answer three questions:

1. Should it be recommended to Canadian citizens to purchase certain types of CFLs, such as amalgam and/ or covered CFLs, based on safety and performance characteristics?
2. Based on the health risks associated with breaking a CFL lamp, is it appropriate to reduce or simplify the currently recommended CFL clean up procedures (regardless of mercury type used in the lamp)?
3. Should a second phase of this study be conducted to make laboratory measurements, such as of mercury release from CFLs?

The LRC addressed the first question by comparing the results of studies in which CFLs were broken with acute and chronic mercury vapor health limits. Based on the reviewed studies, a Canadian citizen following recommended procedures for cleaning up a broken CFL will not be exposed to a great enough mercury vapor concentration to violate any identified acute or chronic exposure limits. If a person is unaware that a CFL has broken in a room or does not follow recommended clean up procedures to open a window and leave the room for 15 minutes, the short term mercury exposure will still be below most acute exposure limits. In less than half of the test cases reviewed, mercury concentrations exceeded California's Office of Environmental Health Hazard (CA OEHHA) REL one hour acute exposure limits, which is two orders of magnitude lower than the next lowest acute exposure levels. (Most of this average exposure level is caused by the initial peak, so if the person is out of the room for 15 minutes per the recommended procedure, the actual one hour average exposure experienced by the person will be much lower.) Even if the broken CFL is never cleaned up, within eight days evaporation and room air changes will reduce the mercury concentration below the lowest chronic level the LRC identified.

In the reviewed studies, amalgam CFLs were found to result in mercury concentrations six to 28 times lower than non-amalgam mercury CFLs when broken.

Based on the low likelihood that even a broken bare spiral non-amalgam mercury CFL will exceed acute or chronic mercury concentration limits, it is not necessary for the Canadian government to recommend the purchase of special CFLs. However, if Canada were to use caution with regard to the uncertainties associated with the health effect of mercury exposure on fetuses and young children, the recommendation might be made to choose shatter-proof, covered, or amalgam CFLs or alternative light sources in households with pregnant women or small children. This is consistent with a recommendation made by Stahler et al.

To answer the second of the three questions above, the LRC reviewed Health Canada's CFL clean up procedures provided at http://www.hc-sc.gc.ca/hl-vs/iyh-vsv/prod/cfl-afc-eng.php. The LRC found these procedures to be up-to-date and reflective of the findings of the recent studies discussed in this report. Reducing or simplifying the procedures may result in increased exposure to mercury vapor by people following those procedures.

Because of the difficulty in cleaning up a broken CFL from a carpet without a vacuum cleaner, NRCan may wish to suggest that, covered CFLs or non mercury-bearing light sources be used (e.g., LEDs, incandescent) in carpeted areas.

The LRC believes that further study is not needed to provide answers to the first two questions above. Two recent studies that measured the mercury vapor concentration in a typical room as a result of CFL breakage were reviewed, and they appeared to be realistic and thorough, and their results agree with one another. The primary question that still needs to be answered is what is a safe mercury exposure limit for fetuses, infants, and young children. This is a question more appropriate for the fields of medicine and toxicology rather than lighting research.

Although not necessary to answer the first two questions above, NRCan might consider two laboratory experiments in a second phase of this study:

- It may also be helpful to NRCan to conduct research on the protective effects of the outer bulb of covered CFLs. As discussed in this report, they were found to be effective in reducing breakage when dropped onto carpet, but how effective are they when dropped on hard flooring and when struck by another object? Also, most covered CFLs have a glass outer bulb, but one covered CFL product provided by NRCan for testing (ClearLite ArmourBulb) had a polymer outer bulb and its packaging claimed that the coating was intended to prevent mercury from escaping and that it is safe to use near "children, elderly, pets, and pregnant women." It may be useful to test this product in particular against its marketing claims and determine if the plastic outer bulb yellows with age or accumulates more dirt than glass bulbs (because it has a high friction coefficient). Note that this lamp is sold for $6.45 (via Amazon.com as of April 2012), which is more expensive than typical non-dimming CFLs.
- Studies reviewed for this investigation found inconsistent results regarding the effect of operating temperature on mercury concentration upon breakage. NRCan might be interested in further refining its understanding of this issue. If operating CFLs are consistently found to produce higher mercury vapor concentrations upon breaking, then this multiplier should be incorporated into the exposure limit comparisons.

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Appendix A: Summary of Reviewed Articles

(Aucott, McLinden, & Winka, 2003)

As research scientists for the New Jersey Department of Environmental Protection, the authors were primarily concerned with large-scale commercial lamp waste from linear fluorescent lamps, rather than accidental breakage of CFLs in the residential context. They sought to recreate a scenario in which discarded lamps are stored in an uncovered garbage receptacle while awaiting final disposal. They tested mercury release from broken, spent linear fluorescent lamps. Their samples were all low-mercury, Philips Alto (green label) F40 T12 lamps. Aucott et al. found that mercury content was continuously volatized over a time period greater than 2 weeks after breakage. Only 17-40% of mercury content was volatized in this time period; the research was not designed to predict total time necessary to volatize total Hg. Higher temperatures resulted in proportionally higher release rates. One-third of the total measured mercury vapor release occurred within the first 8 hours after breakage. It can be inferred from these data that removal of spent lamp debris is important to minimize exposure hazard.

(Beate, Stephan, & Gustav, 2010)

Journal article that provides alternative case studies for human exposure to mercury vapor and provides recommended reference concentration (RfC) based on this data set. RfC criteria proposed is 88% lower than Health Canada provisional value and 77% lower than US EPA value. Differences in RfC values from these other standards are based on difference in both LOAEL values and selected UF.

(Bernhoft, 2012)

Journal review article provides detailed overview of mercury exposure effects on humans for all three types of mercury. Report states that most human exposure results from fish consumption, exposure to mercury vapor through outgassing from dental amalgams and occupational exposure. Relative absorption mechanism of inorganic mercury: 80% of mercury vapor is absorbed through inhalation, 7 - 10% is absorbed via ingestion. 1% is absorbed via dermal contact Mercury vapor is transported to the brain and chronic exposure to high levels of mercury vapor results in neurological dysfunction. Low level chronic exposure leads to various non-neurological symptoms including fatigue, weight loss, weakness and gastrointestinal disturbances.

Acute exposure to large amounts of mercury vapor leads to respiratory distress, which can be fatal. Cessation of exposure may lead to symptoms disappearing but persistent neurological symptoms are common.

About 80% of methylmercury vapor is absorbed via inhalation. Unlike ingestion or dermal absorption of elemental mercury, methylmercury is efficiently absorbed and ingested.

(Bose-O'Reilly, McCarty, Steckling, & Lettmeier, 2010)

Adverse effects from acute or chronic mercury exposure will occur for all humans. However, children are at particularly high risk because of developmental vulnerabilities, lower body weight, childhood behaviors (such as playing with soil and placing their hands in their mouths) and because of their attraction to elemental's mercury's physical appearance.

Fetuses and infants are especially vulnerable to mercury exposure because they are developing their central nervous systems. For these subpopulations, mercury exposure can cause permanent damage to the nervous system.

There is no safe exposure level that has been identified.

(Clear & Rubinstein, 2009)

This article compares mercury exposure from CFL breakage with mercury exposure from eating tuna fish. The summary of the article is "The potential perils have been played up in the press, but if simple common sense is used when disposing of a broken CFL, the resulting exposure to mercury is equivalent to a mere nibble of tuna." However, because of the differences between methyl- and elemental mercury, it is inaccurate to directly compare methylmercury exposure to elemental mercury exposure, as was conducted in this article. (Also, there is a range of methylmercury exposure through fish consumption.)

(Corazza, Giorgi, & Massaro, 2011)

This paper discusses main amalgams, auxiliary amalgams, getter alloys, and dosing alloys.

The optimum mercury vapor pressure in CFLs is in the range of 0.8 to 1.5 Pa, which is reached when the cold spot temperature is 40 to 50 C. The "main" or "working" amalgam is used to maintain the mercury vapor pressure at operating temperature. The mercury vapor pressure has a plateau in the temperature range when the solid and liquid phases of the formed amalgam coexist. The main amalgam is coated on an In-Ag or In-Sn alloy flag. When the main amalgam is InAg-Hg, the optimum mercury vapor pressure is achieved in the temperature range of 105-140 C. When the main amalgam is InSn-Hg, the optimum mercury vapor pressure is achieved in the temperature range of 95-125 C. The mercury vapor pressure is a function of the amalgam used, the cold spot temperature, and the mercury concentration (weight-percent).

The auxiliary amalgam decreases the run-up time of an amalgam lamp. It is on an auxiliary amalgam flag, "typically an indium-plated metallic strip or an In- based alloy coated flag mounted close to the electrode." It is "used to capture mercury atoms after the lamp switches off and to quickly release them immediately after the switch-on."

A dosing amalgam is used to more precisely control the amount of mercury added to CFLs. The dosing alloy Ti-Hg is "well known," and allows reliable dosing even less than 1 mg. After the lamp is sealed, thermal activation is used to release the mercury.

A getter alloy is used to absorb impurities in the fill gas, which can adversely affect lamp performance.

(Corazza et al., 2008)

This paper describes new dosing alloys for CFLs. The paper claims that mechanical liquid dosing (an old method) is inaccurate. Newer methods include using unstable dosing amalgams like Zn-Hg and Sn-Hg spheres which are introduced into the exhaust tube of the CFL before sealing. The authors claim that the "the variability of the Hg dose from these unstable products is, in general, too high for low content fluorescent lamps." Another method is "glass capsule technology" in which a vial of mercury is put inside the CFL and then ruptured with a heated wire after the CFL is sealed.

The authors say that stable mercury dosing amalgams such as Ti-Hg provide better accuracy. These are sealed inside the CFL and then the mercury is released by using RF to heat the amalgam to 900C. A promoter based on Cu-Sn compound increases the fraction of mercury in the dosing amalgam that is released. A getter such as Zr-Al is combined with this dosing amalgam.

(dos Santos et al., 2010)

This group of Brazilian researchers sought to quantify Hg. They worked with U-bend and spiral-shaped compact fluorescent lamps, both new and spent. They did not focus on quantifying Hg vaporization rates, but rather quantifying total elemental Hg. They found that Hg mass ranged widely, from 1.6 mg - 27 mg. New and spent lamps were not matched models, so the reader cannot generalize about the impact of lamp use on Hg quantity. The researchers found some new lamp samples that exceeded the European Community's limit of 5 mg; none of the spent lamps exceeded this limit.

(Heidemann et al., 1993)

This paper discusses the general design and operation of CFLs. It notes that optimum luminous efficacy is achieved when the mercury vapor pressure is in a small range around 0.006 hPa, which is equal to 0.6 Pa, and this requires a "cold spot" temperature of approximately 40 degrees C (presumably for non-amalgam mercury).

(IESNA, 2011)

This compendium resource summarizes the features of mercury that necessitate its use in fluorescent discharge lamps. Because vaporized mercury is required to sustain the arc, depletion of mercury is one of the two main fluorescent lamp failure modes. Vaporized mercury condenses on the bulb wall, and may melt and be trapped in the glass. In the past, manufacturers provided larger amounts of mercury to extend lamp life. But recently manufacturers have developed "barrier" technologies (e.g. alumina, magnesium, titanium, etc.) that not only reduce absorption by glass, but also provide other benefits, such as improved lumen maintenance.

(Jang, Hong, & Park, 2005)

This group of researchers from Wisconsin, USA, measured Hg mass from spent T8 and T12 linear fluorescent lamps, as well as new T12 lamps. This work was focused on large-scale commercial solid waste context, rather than residential CFL accidents. The researchers examined Hg in vapor phase, loose phosphor, endcaps, and glass lamp matrices. No samples utilized a mercury amalgam, as this is not commonly available in linear fluorescent lamps. None of their lamp samples were a shatter-resistant nor covered type. Jang *et al*. found that nearly all (94-97%) of the elemental mercury in spent lamps is absorbed in the phosphor and the lamp glass. Mercury vapor was undetectable in spent T8 lamps. While vaporized mercury was 4x higher for new T12 lamps than spent T12 lamps, vaporized Hg in T12 lamps was still found to be less than 1% of total Hg content. Another author (see Johnson et al. 2008) points out that Jang's research focuses here on partitioning of mercury; when a lamp breaks, mercury imbedded in lamp architecture is gradually evaporated and rereleased as vapor. Because elemental mercury is predominantly absorbed by lamp architecture, it can be inferred that removal of broken lamp debris (before mercury vapor is re-released) is important to minimize exposure hazard.

(Johnson, Manchester, Sarin, Gao, Kulaots, & Hurt, 2008)

The goal of this research was to characterize the release of Hg vapor from CFLs as a function of time since fracture, and to evaluate new materials that could be used in the clean-up process. They tested both new and used CFLs. They found that immediate removal of large pieces of CFL debris reduced mercury release rates by two-thirds; the remaining third of Hg vapor release was attributed to phosphor powder that scattered across a carpet surface. Nearly complete suppression of mercury vapor was achieved by sealing a broken lamp in a confined space with unstabilized nano-selenium. The authors are presently developing technology that could eventually be used as a commercial product for in situ cleaning of broken CFLs. This type of product would consist of a cloth impregnated with nano-Selenium, nano-Silver, or sulfur-impregnated activated carbon.

(Lankhorst & Niemann, 2000)

This paper discusses the thermodynamic theory of amalgams for CFLs.

The optimum mercury vapor pressure for CFLs is 1 to 2 Pa. "Well known" amalgams used in CFLs are BiInHg and BiPbSnHg. Most amalgams used in CFLs are solid at room temperature. For CFLs, the minimum bulb wall temperature is between 60 and 130 C. As CFLs are made smaller, the MBWT is expected to rise to 100 to 170 C, so different amalgams will be needed to keep the mercury vapor pressure in the optimum range.

Amalgams are used to stabilize the mercury vapor pressure because at the CFL operating temperature the components of the amalgams are at different phases (e.g. at least one component is a solid and at least one component is a liquid) and much of the energy from a temperature change goes to changing the phase of an amalgam component rather than to changing the vapor pressure of mercury.

(Lankhorst et al., 2000)

The optimum mercury vapor pressure in CFLs is typically 1 to 4 Pa. An ideal amalgam would provide the vapor pressure of pure mercury at room temperature but low mercury activity at operating temperature. At the time the paper was written, common amalgams were Bi-In and Bi-Pb-Sn.

This paper proposes new amalgams for CFLs based on thermodynamic theory. The current market trend is toward smaller CFLs, which will operate at higher temperatures. The proposed amalgams will maintain the desired mercury vapor pressure at higher temperatures than previously used amalgams. The proposed amalgams are Bi-Pb-Hg and Bi-Pb-Au-Hg.

(Li & Jin, 2011)

The researchers from Mississippi, USA, measured mercury release in the CFL context. While the researchers evaluated leaching (relevant for landfill conditions) and precipitation leaching (relevant for rainwater), they also evaluated total Hg and vaporized Hg. Leaching and total Hg were measured for 8 brands of CFLs, ranging from 7-42 W. They included mostly spiral lamps; two were covered-type A-lamp shape. Most samples were new lamps; one had been in residential use for about 3 years. Li *et al.* found that Hg concentrations varied widely with manufacturer (0.1-3.6 mg). The lowest Hg mass was found in the covered lamp samples (0.1 mg and 0.2 mg). Contrary to expectation, the older, used CFL sample actually had greater Hg mass than its new equivalent; the authors conjecture that this is due industry pressure to reduce Hg amounts in new lamps.

The researchers tested Hg vapor release for three lamps with equivalent wattage. Li *et al.* found that Hg vapor continued to be released for greater than 43 days (if debris is not removed from the space); they predict continued release for 53, 92, and 128 days, respectively, for the three samples tested. Several weeks after being broken, cumulative mercury vapor amounts exceeded 1.0 mg. This shows that allowing broken CFLs to remain in the environment could result in exposure levels that exceed safe human exposure limits.

(Miller et al., 2002)

Report discusses risk assessment methodologies used by California EPA to determine recommended exposure levels for various toxicants. With regard to mercury exposure the report provides the following information. Mercury exposure is potentially greater for young children. Breathing rates per unit of body weight is higher in infants and young children than in adults (5 years old and younger)

Because Mercury vapor is heavier than air, and breathing rates are higher in children, children are more susceptible to mercury poisoning than adults. CDC notes one case study where children were affected with acute mercury poisoning in household but adults in the same household were not affected.

Children have smaller airways, which tend to have increased particle deposition compared to adults. Particle deposition model for lungs is predicted to have inverse relationship to body size (from Phalen et al. 1985)

(National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances, 2010)

This paper provides definitions of terms related to mercury exposure including:

AEGL (acute exposure guideline levels) define threshold exposure limits for the general public, including susceptible populations, based on exposures to airborne substances that occur on an emergency basis (rare occurrences)
"AEGL-1 - threshold for airborne concentration level above which a transient non-disabling effect is produced.
AEGL-2 - a threshold for airborne concentration level above which an irreversible or long-lasting adverse effect is produced.
AEGL-3 - a threshold for airborne concentration level above life-threatening health effects or death could occur."

(Northeast Waste Management Officials' Association (NEWMOA), 2008)

This paper provides the amount of mercury used in CFLs in 2004 based on NEMA data. At that time, 66% use 0 to 5 mg, 30% used 5 to 10 mg, and 4% used 10 to 50 mg.

This paper states that the Maine study of mercury exposure from broken CFLs was influential and resulted in the change of recommended clean up procedures from the EPA and several states.

(Richardson et al., 2009)

Journal article that provides review of human occupational studies that form the basis for several international chronic mercury exposure guidelines. Authors use alternative human occupational studies to determine recommended exposure limit (REL) for Health Canada.

(Salthammer, Uhde, Omelan, Lüdecke, & Moriske, 2011)

The researchers built an apparatus to shatter CFLs in a controlled manner. They tested mercury release from 6 CFL lamp types, from 3 manufacturers available in Germany. One sample had a shatter-resistant coating, and one sample contained a mercury amalgam. They did not test a covered-type lamp shape. All lamp samples were new. The researchers measured mercury concentration (ng/m3) at a baby's height (30 cm) and child's height (100 cm). They evaluated lamps that were both recently operated ("hot") and "cold", over the course of 2+ days. They performed their data collection above carpet, laminate flooring, and a plastic-type tray. Their results showed that the best (lowest) peak vaporized Hg concentration occurred with the shatter-resistant lamp, for both hot and cold breaks. The amalgam lamp sample exhibited next lowest Hg concentration. The amalgam(s) used in the tested CFLs is not specified. The other lamp types showed mercury concentrations similar to previous research results. Airborne Hg demonstrated peak concentration immediately after lamp breakage. The researchers did not find a consistent trend in hot breaks vs. cold breaks; in some cases the cold lamp created higher initial Hg concentrations than its hot equivalent. Higher mercury concentrations tended to be found with laminate flooring than with carpet. Ventilation considerably reduced mercury concentration.

Key findings:

- "Acute adverse health effects from exposure to mercury after accidental breakage of a CFL are unlikely if immediate protective measures are taken."
- "Shatter-proof CFLs and amalgam-type lamps offer considerably better protection against mercury contamination in the indoor environment."

(Sandborgh-englund et al., 1998)

Sandborgh-Englund et al**.** exposed nine humans to 400 µg/m^3 of mercury vapor (Hg^0) for 15 minutes. Using 30 days of sampling of urine, blood and exhaled air, researchers found that the median amount of Hg^0 retained was 69%.Researchers also found that amount of Hg0Hg^0 inhalation from amalgam fillings (typical amount of fillings per mouth) was 5-9 µg/day.

(Serres & Taelman, 1993)

This paper discusses CFL design choices, including the use of amalgams. It describes the mechanisms by which CFLs work and by which the minimum bulb wall temperature controls the light output. It gives the mercury vapor pressure vs. amalgam temperature for two unnamed amalgams, one binary (two components) and one ternary (three components).

The design goal for CFLs is to control the mercury vapor pressure to maximize light output. Using amalgams allows the light output to be optimized over a wider temperature range and in different operating positions.

CFLs with elemental (liquid) mercury use "modified bulb wall configuration control" of mercury vapor pressure in which a portion of the bulb is designed to be farther from the discharge than the rest of the bulb, which yields a cool spot, which controls the vapor pressure. Modified bulb wall configuration control works for bulb wall temperatures up to 60 degrees C.

The other way to control the mercury vapor pressure is by using amalgams. Design considerations include the specific main amalgam to use, the mercury content of the main composite, and the use of an auxiliary composite. The paper states that the most commonly used amalgam is an unnamed binary with a 3% mercury content. In a diagram, the amalgam is shown as a sphere located below the electrode at the end of an exhaust tube.

A downside to using amalgams is that they cause slow run-up time. This is countered by using an auxiliary amalgam on a flag located close to an electrode for fast temperature rise. The auxiliary amalgam has a lower mercury vapor pressure than the main amalgam at equal temperatures to permit the absorption of mercury when the CFL is off. When the CFL is turned on, the mercury in the auxiliary amalgam is freed and precipitates on the nearby bulb wall. As the bulb wall near the electrode heats up, this mercury then vaporizes. After all of the mercury is vaporized, the vapor pressure is held constant by the main amalgam absorbing some mercury. (i.e. The main purpose of the main amalgam is to absorb mercury to maintain a constant vapor pressure.) "During the on-time of the lamp, the mercury is almost totally absorbed by the main amalgam and auxiliary amalgam is almost mercury-free." After the CFL is turned off, the auxiliary amalgam absorbs mercury until the vapor pressure equals the vapor pressure controlled by the main amalgam. In the first 8 to 16 hours after being turned off, the mercury content of the auxiliary amalgam rises to 20%, but then continues to rise for the next 100 hours until equilibrium is reached. This implies that in the off state, the mercury vapor pressure takes days to reach equilibrium.

(Stahler, Ladner, & Jackson, 2008)

Researchers in Maine, USA, undertook extensive research to characterize mercury vapor release from several different scenarios of broken CFLs, as well as several clean-up procedures.

While this research did show less mercury vapor release from amalgam-type lamps compared to non-amalgam lamps, the authors did not test enough amalgam samples to generalize about the relative safety of these lamps.

Variability among CFL models was significant, but in general, mercury concentrations are rapidly improved (decreased) with venting and cleanup of debris. Venting the room in which the CFL break occurred dramatically reduced concentration of mercury vapor. However, someone entering the room immediately after breakage will likely be exposed to highest levels of mercury, so the authors recommend waiting 15 minutes before clean-up.

Another key finding is that mercury vapor from lamp debris is not suitably contained by plastic garbage bags. This research shows that the best choice for storage and disposal of lamp debris is a glass container with a metal screw lid and gum seal.

This research did find that mercury will continue to vaporize from flooring material. Thus environments with sensitive populations (children, pregnant women) may be best addressed with removal of carpeting in the affected area.

This study strongly warns against use of vacuum cleaners, as they agitate and promote vaporization of mercury. It is expected that mercury will be re-distributed in the room from re-vacuuming, and may contaminate the vacuum cleaner, thus distributing mercury vapor throughout the house.

In summary, the authors recommended changing the Maine Department of Environmental Protection cleanup guidance to include:

1. Leaving the area/room and waiting 15 minutes after breakage to begin cleaning up (mercury levels in the air will have fallen from their highest levels by then);
2. Using a glass container with a metal screw top lid with seal such as a canning jar to contain the lamp pieces, powder, and cleanup materials;
3. Immediately removing the containerized lamp debris from the living quarters especially if the homeowner did not have a glass container with a good seal;
4. Continue venting room for several hours;
5. Suggesting that homeowners consider removal of carpeting sections where breakage has occurred as a precaution in some situations, particularly in homes with infants, small children or pregnant women;
6. If carpet is not removed, the homeowner should consider ventilating the room during vacuuming for the next several vacuuming events;
7. Suggesting that homeowners consider not utilizing fluorescent lamps in situations where they could easily be broken, in bedrooms used by infants, small children

or pregnant women, or over carpets in rooms frequented by infants, small children or pregnant women; and

8. Avoiding the storage of too many used/spent lamps before recycling that could increase the chances of breakage.

(Tunnessen et al., 1987)

This is a report of a case study of 23 month old infant playing in potting shed where a case of 8 foot fluorescent lamps had broken 5 months earlier. No other sources of mercury were in the home.

Mercury levels in air samples were 5 - 62 $\mu g/m^3$, with vacuum cleaner noted as having highest mercury level in air sample (unclear if when they vacuumed the Hg levels increased). Traces of mercury found in potting shed soil and siblings bedroom carpet.

All family members had elevated mercury levels (> 20 ng/ML which is normal level in adults). No other family members had symptoms of mercury poisoning.poisoning

Patient had acrodynia - "painful extremities". Acrodynia symptoms are described as “red puffy hands and feet with peeling skin.”. Other common comorbid symptoms with acrodynia include anorexia, insomnia, irritability, profuse sweating and resulting malaria like rashes, photophobia.

(United States Environmental Protection Agency, 2011)

Webpage explains chronic health hazard assessments for noncarcinogenic effects.

Reference Concentration for Chronic Inhalation Exposure for elemental mercury (RfC) - estimate of the daily human inhalation exposure that will likely not to appreciably increase risk of deleterious effects over a lifetime.

RfC: 0.0003 mg per cubic meter. UF (uncertainty factor) is 30, where UF is used to account for protection of protection of sensitive human subpopulations, including accounting for acrodynia.

EPA also provides an adjusted LOAEL (lowest observed adverse effect level) exposure limit of 0.009 mg per cubic meter based on an 8 hour 5 day TWA (time-weighted average) occupational exposure. This value is based on human occupational inhalation studies.

LOAEL is defined as "The lowest exposure level at which there are biologically significant increases in frequency or severity of adverse effects between the exposed population and its appropriate control group"

EPA lists the critical effects of mercury vapor exposure as hand tremors, increases in memory disturbance, slight autonomic dysfunction.

EPA has no reference dose at this time for chronic oral exposure (RfD) for elemental mercury.

For methylmercury, EPA has RfD of 1 μg/kg body weight per day as the exposure level without adverse effects.

EPA does not provide an NOAEL (no observed adverse effect level).

(United States Environmental Protection Agency, 2010b)

This paper provides a synopsis of mercury health effects by EPA.
There are three chemical forms of mercury - organic methylmercury, elemental mercury and mercury compounds (organic and inorganic).

Health effects from mercury are dependent on chemical form, dose, age of exposed person, duration of exposure, route of exposure, health of exposed person.

The primary exposure to mercury for people living in the US is via organic methylmercury found in fish and shellfish. Methylated mercury in the aquatic environment is found in fish and seafood with higher accumulation found higher up the food chain.

Health effects:
Methylmercury - Fetuses, infant and children are at highest risk and primary effect is impaired neurological development. Recent CDC monitoring shows that most women of child-bearing age and children have levels of mercury in blood that are below the threshold for possible health effects (MMWR 2004).

Elemental mercury - Health effects are of most concern when mercury vapor is inhaled and is then absorbed by lung tissues. Spills or accidental release of elemental mercury create mercury vapor. Potential health effects are highest when mercury vapor is contained in a warm or poorly ventilated environment. Health effects include: tremors, insomnia, neuromuscular changes, headaches, neurological effects (cognitive deficits changes in nerve responses, disturbances in sensations). Higher elemental mercury exposure can lead to kidney failure, respiratory failure and death.

Mercury compounds, such as mercuric chloride are typical absorbed via ingestion and dermal contact. Health effects include damage to intestinal tract, nervous system and kidneys. Organic mercury compounds are readily absorbed via ingestion than inorganic mercury compounds. Symptoms of high exposure include rashes and dermatitis, neurological effects (memory loss, mental disturbances, mood swings) and muscle weakness.

(United States Environmental Protection Agency, 1997a)

Three valance states of mercury
1. Hg^0 - elementalelemental mercury
2. $Hg^{2\ 2+}$ - mercurous mercury
3. Hg^{2+} - mercuric mercury

Document provides detailed research summaries, hazard identification and dose-response assessments for elemental mercury, inorganic mercury (mercuric chloride) and organic mercury (methylmercury). These are predominant forms of mercury for which people are exposed. Exposure can occur via inhalation, ingestion of contaminated food, water or soil, dermal exposure, and mercury vapor from dental amalgams

(Vidich & Grover, 2005)

This study, by URS Inc. and the United States Postal Service found that up to four CFLs could be broken without exceeding ACGIH and NIOSH ceiling guidelines.

Appendix B: Results of Stahler and Salthammer Papers

Study		CFL				Room			Method to Break CFL	Hg Peak concentration after breakage (ng/m^3)	Hg concentration after ventillation but before cleanup (ng/m3)	One hour average concentration (ng/m3)	Hg concentration after cleanup				Notes
		Type	Hg amount (mg)	Hg type	Condition at break	Volume (m^3)	Flooring	Window					Concentration (ng/m3)	Time of measurement (h)	Cleanup		
Author	Experiment														Elapsed time from breakage to cleanup	Method	
Salthammer	Series 2	Bare spiral	1.5	NS	Off/ cold	68	Laminate	Open	Hammer	1000	12	NS	6	20.7	25	wipe	Followed recommended procedure of opening window at time of breakage and venting before cleanup.
Salthammer	Series 2	Bare spiral	1.5	NS	Off/ cold	68	Carpet-loop pile	Open	Hammer	5740	12	NS	19	3	20	vacuum	Followed recommended procedure of opening window at time of breakage and vented before cleanup, but used vacuum cleaner.
Salthammer	Series 3	11W	1.9	NS	Off/ cold	24	Carpet	NA. Air change 0.5/h	Steel Rod	200	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	1.9	NS	Hot/ on for 1 h prior to break	24	Carpet	NA. Air change 0.5/h	Steel Rod	6000	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	20W, shatter-resistant	2	NS	Off/ cold	24	Carpet	NA. Air change 0.5/h	Dropped	60	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	20W, shatter-resistant	2	NS	Hot/ on for 1 h prior to break	24	Carpet	NA. Air change 0.5/h	Dropped	5	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	1.5	NS	Off/ cold	24	Carpet	NA. Air change 0.5/h	Steel Rod	1000	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	1.5	NS	Hot/ on for 1 h prior to break	24	Carpet	NA. Air change 0.5/h	Steel Rod	3000	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	1.5	NS	Off/ cold	24	Laminate	NA. Air change 0.5/h	Steel Rod	1000	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	1.5	NS	Hot/ on for 1 h prior to break	24	Laminate	NA. Air change 0.5/h	Steel Rod	9000	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	2	Amalgam	Off/ cold	24	Carpet	NA. Air change 0.5/h	Steel Rod	100	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	2	Amalgam	Hot/ on for 1 h prior to break	24	Carpet	NA. Air change 0.5/h	Steel Rod	200	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	2	Amalgam	Off/ cold	24	Laminate	NA. Air change 0.5/h	Steel Rod	400	NA	NS	NA	NA	NA	NA	
Salthammer	Series 3	11W	2	Amalgam	Hot/ on for 1 h prior to break	24	Laminate	NA. Air change 0.5/h	Steel Rod	200	NA	NS	NA	NA	NA	NA	

NS= Not Specified. NA= Not applicable. All CFLs were new/ unused. Measurement height is 0.3 m above ground.

Study		CFL				Room			Hg Peak concentration after breakage (ng/m^3)	Hg concentration after ventillation but before cleanup (ng/m3)	One hour average concentration (ng/m3)	Hg concentration after cleanup				Notes
														Cleanup		
Author	Experiment	Type	Hg amount (mg)	Hg type	Condition at break	Volume (m^3)	Flooring	Window				Concentration (ng/m3)	Time of measurement (h)	Elapsed time from breakage to cleanup	Method	
Stahler	Scenario S1	Philips Energy Saver 60 14W covered CFL	NS	Not specified, but maybe amalgam because CFL is covered	Off/ cold	39	Wood	Closed	8533 to 34954	<300	624	NA	NA	60	NA	Did not follow recommended procedure because window was closed.
Stahler	Scenario S2	Philips Energy Saver 60 14W covered CFL	NS	Not specified, but maybe amalgam because CFL is covered	Off/ cold	39	Wood	Open	17569	<300	199	<50	1.7	0	broom, tape, wipe	Did not follow recommended procedure because did not vent room before clean up, so peak value is not applicable, but long-term results may be relevant.
Stahler	Scenario SA	General Electric 26W	NS	NS	Off/ cold	39	Wood	Open	61037	<300	1398	<50	6.6	1	broom, tape, wipe	Did not follow recommended procedure because did not vent room before clean up, so peak value is not applicable, but long-term results may be relevant.
Stahler	Scenario SC	N:Vision 14W bare spiral	NS	NS	Off/ cold	39	Wood	Open	27224	<300	684	<50	4.1	2	broom, tape, wipe	Did not follow recommended procedure because did not vent room before clean up, so peak value is not applicable, but long-term results may be relevant.
Stahler	Scenario SD	Philips Energy Saver 60 14W covered CFL	NS	Not specified, but maybe amalgam because CFL is covered	Hot/ on for 1 h prior to break	39	Wood	Open	12016	150	123	<50	5.9	1	broom, tape, wipe	Did not follow recommended procedure because did not vent room before clean up, so peak value is not applicable, but long-term results may be relevant.
Stahler	Scenario SE	General Electric 26W bare spiral	NS	NS	Off/ cold	39	Wood	Open	65094	400	1048	<300 "Several spikes over 50 ng/m3 but less than 300 ng/m3"	2.8	1	broom, tape, wipe	Did not follow recommended procedure because did not vent room before clean up, so peak value is not applicable, but long-term results may be relevant.
Stahler	Scenario SF	General Electric 26W bare spiral	NS	NS	Off/ cold	39	Wood	Open	54142	NA	2745	NS	NS	46	broom, tape, wipe	Followed recommended procedure of opening window at time of breakage and venting before cleanup.
Stahler	Scenario SG	N:Vision 23W bare spiral	NS	NS	Off/ cold	39	Wood	Open	8603	<300	377	<50	0.5	11	broom, tape, wipe	Followed recommended procedure of opening window at time of breakage and venting before cleanup.
Stahler	Scenario SH	Lightwiz 15W bare spiral	NS	NS	Off/ cold	39	Wood	Open	17178	<300	263	<50	1.5	5	broom, tape, wipe	Followed recommended procedure of opening window at time of breakage and venting before cleanup.
Stahler	Scenario SI	Greenlite R30 (covered) 15W	NS	Amalgam	Off/ cold	39	Wood	Open	687	<300	70	<50	1.7	7	broom, tape, wipe	Followed recommended procedure of opening window at time of breakage and venting before cleanup.
Stahler	Scenario SJ	Philips Energy Saver 60 14W covered CFL	NS	Not specified, but maybe amalgam because CFL is covered	Off/ cold	39	Wood	Open	7412	<100	133	<50	0.9	1	broom, tape, wipe	Did not follow recommended procedure because did not vent room before clean up, so peak value is not applicable, but long-term results may be relevant.
Stahler	Scenario S3	Philips Energy Saver 60 14W covered CFL	NS	Not specified, but maybe amalgam because CFL is covered	Off/ cold	39	Carpet-short pile	Open	10788	<300	142	<50	10	0	broom, tape, wipe	Did not follow recommended procedure because did not vent room before clean up, so peak value is not applicable, but long-term results may be relevant.
Stahler	Scenario S4	Philips Energy Saver 60 14W covered CFL	NS	Not specified, but maybe amalgam because CFL is covered	Off/ cold	39	carpet-long pile "shag"	Open	22176	<300	159	<50	9	0	broom, tape, wipe	Did not follow recommended procedure because did not vent room before clean up, so peak value is not applicable, but long-term results may be relevant.

NS= Not Specified. NA= Not applicable. All CFLs broken with a hammer. All CFLs were new/ unused. Measurement height is 0.3 m above ground.

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