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Screening Level Risk Characterization for Mercury Exposure from Compact Fluorescent Lamps

Prepared for:

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The opinions expressed in this text are those of the authors for the purposes of protecting public health. These authors' opinions do not necessarily represent the views of the sponsors, ESR and NZ Ministry of Health.

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TERA performed this work under contract with the Institute of Environmental Science and Research Limited (ESR) for the New Zealand Ministry of Health. However, the opinions expressed in this text are those of *TERA* for the purposes of protecting public health. These opinions do not necessarily represent the views of the sponsors, ESR and NZ Ministry of Health**.**

Furthermore, this project was conducted under the auspices of the Alliance for Risk Assessment (*ARA*), a collaboration of diverse stakeholders representing government, academic, industry, environmental and consulting perspectives. All projects are vetted to promote scientific relevance and avoid duplication of effort. As an *ARA* project, this assessment was conducted by an independent, nonprofit organization, using state-of-the-science chemical risk assessment methods to protect public health. *ARA* risk assessments are performed in an open and transparent manner, and made publically available upon completion at www.allianceforrisk.org.

Purpose of this Report

The purpose of this report is to provide a screening level risk characterization of mercury released from breakage of compact fluorescent lamps (CFLs). A screening risk characterization typically includes scenarios intended to maximize potential exposures, and health risk benchmark values that maximize potential to protect public health. These two efforts ensure that the resulting screening level risk characterization is conservative and protective of public health. When screening level risk characterization targets are exceeded, the appropriate next step is to refine the exposure estimates and evaluate more closely the benchmark values to better characterize the risk. If the estimated risk is of concern, then risk management options might be considered. As this is a screening assessment, the second and third steps are not address here. This report discusses:

- Type(s) of mercury in CFLs
- Available information on the variation of mercury levels among CFLs
- Two exposure assessment scenarios, specifically,
    - single CFL breakage small room of X size, no ventilation, no clean up (worst case scenario),
    - single CFL breakage small room of X size, adequate clean up carried out and adequate ventilation; ongoing mercury release from carpet following clean up, etc.
- Latest health risk benchmark values (e.g., RfC, for the type of mercury in CFLs).
- Calculation of risk to child and adult based on typical exposure parameters and assumptions and use of standard risk characterization techniques such as Hazard Quotient.
- Brief discussion of uncertainties and areas for additional evaluation.

Introduction

Fluorescent lamps including fluorescent tubes and compact fluorescent lamps (CFLs) are increasingly being used in New Zealand houses as part of a drive to improve energy efficiency. Their use is promoted as just one option as a replacement for incandescent lamps by government agencies including the Ministry for the Environment, the Energy Efficiency and Conservation Authority and the Electricity Commission. Fluorescent lamps are more efficient at converting electricity into light and can be substituted for some incandescent light bulbs without altering existing light fittings.

The key advantages of installing CFLs compared with incandescent lamps are large reductions in energy use and greenhouse gas emissions if the electricity is produced from burning fossil fuels (Parsons, 2006). A disadvantage of fluorescent lamps is that they contain milligram quantities of mercury. Mercury is an integral component of fluorescent lamps and a substitute chemical has not yet been identified. Internationally, concerns have been raised regarding potential mercury

exposures following bulb breakage (Stahler et al., 2008; Groth, 2008).

Fluorescent Lamps

Fluorescent lamps are electrical discharge lamps that contain low-pressure mercury vapor and an inert gas, usually argon. The inside of the glass is coated with a fluorescent made with phosphor powder. The mercury vapor is excited by an electrical current between two electrodes and emits UV light. The UV light causes the phosphor coating to fluoresce and emit visible light.

Mercury can be added to lamps in a variety of forms including liquid, solid, or pellet amalgam dosing technology (Parsons, 2006). Both elemental mercury and mercuric oxide have been added to fluorescent bulbs. A variety of mercury amalgams have been used in fluorescent lamps including amalgams with varying combinations of iron, bismuth, indium, tin and lead (Parsons, 2006). During lamp use, the elemental mercury is oxidized and is adsorbed onto the phosphor powder, as well as onto other lamp components including the glass (Raposo et al., 2003; Jang et al., 2005; NJ MTF, 2002; UNEP 2005; Aucott et al., 2003). Elemental mercury also becomes dispersed throughout lamp during lamp operations. These processes reduce the amount of mercury that can be volatilized (NJ MTF, 2002; Aucott et al. 2003). Manufacturers need to add sufficient mercury to ensure that there is an adequate supply of mercury vapor present for the life of the lamp (Raposo et al. 2003; UNEP, 2005).

A range of fluorescent lamps are available in New Zealand including CFLs, circular fluorescent tubes, and linear fluorescent tubes (Energywise, no date). There is no publicly available data on the form of mercury in fluorescent lamps available on the New Zealand market. The focus of this report is on CFLs only.

Amounts of mercury in fluorescent lamps

The amount of mercury present in a fluorescent lamp depends on the type (linear versus CFLs), brand, and the wattage (Aucott et al., 2003; Stahler et al., 2008; Jang et al., 2005; NEWMOA, 2008; Culver, 2008). Reported ranges for amounts of mercury are up to 30 mg per light bulb for CFLs and up to 115 mg for linear fluorescent tubes (Groth, 2008; Jang et al., 2005). Available international data on the mercury content of fluorescent lamps are summarized in Table 1. Lamps with higher mercury contents tend to be less expensive than low mercury content lamps (UNEP, 2005). The amount of mercury per CFL can vary between brands as well as between light bulbs of the same type (Stahler et al., 2008).

Internationally, manufacturers are reducing the amount of mercury used in fluorescent lamps (Energy Star, 2008; UNEP, 2005). In 2007 the National Electrical Manufacturing Association (NEMA) introduced a voluntary cap on mercury content in lamps sold in United States to 5 mg for CFLs less than 25 watts and 6 mg for 25 to 40 watt CFLs (NEMA, 2008). Internationally several manufacturers are producing CFLs with a mercury content of around 1 mg per lamp (Groth, 2008; Culver, 2008).

Table 1.Amounts of mercury present in fluorescent lamps (mg per lamp).

Country	Lamp Type and Amount of Mercury per Lamp (mg)	Reference
Europe	Halophosphate lamps 10	ROHs (2008)
Europe	Triphosphate lamps 5-8	ROHs (2008)
Canada	Linear fluorescent tubes 3-50	Environment Canada (2004)
United States of America	Linear fluorescent tubes 0-100	NEWMOA (2008)
United States of America	Linear fluorescent tubes 1.4-50	Culver (2008)
United States of America	Linear fluorescent tubes 1.25-5.96	Singhvi et al. (2008)
Australia	CFL 0.1 to 13	Boughey and Webb (2008)
Canada	CFL 1-25	Environment Canada (2004)
United Kingdom	CFL <10	AEA Technology (2004)
United States of America	CFL 1-6	Culver (2008)
United States of America	CFL average 4	Energy Star (2008)
United States of America	CFL 5 -50	NEWMOA (2008)

Amounts of mercury in fluorescent lamps available in New Zealand

There are limited data available on the amount of mercury present in fluorescent lamps available in New Zealand. The mercury content is not listed on the packaging for many of the products available in New Zealand and is not always easily accessible from manufacturer's websites. The Electricity Commission (no date) specify a maximum of 5 mg per lamp for CFLs available through the CFL subsidy program. Low mercury CFLs with mercury contents of 1.1 to 1.4 mg per lamp are available in New Zealand (EcoBulb, no date).

It is likely that the amounts of mercury in fluorescent lamps (CFLs and tubes) available in New Zealand are comparable to those available internationally. New Zealand and Australian power supplies have similar voltage of 230v making it likely that the products available in the two countries would have similar mercury contents. The reported range of mercury per lamp for CFLs available in Australia is 0.1 to 13 mg (Boughey and Webb, 2008). Chinese manufacturers of fluorescent lamps export to Australia and the United States (Global Sources, 2008).

Regulatory limits for mercury in fluorescent lamps

Many governments have or are establishing limits on mercury content in CFLs to 5 mg or less (AS/NZS, 2008; Energy Star, 2008; UNEP, 2005; NEMA, 2008; ROHs, 2008).

New Zealand

The Australian/New Zealand Standard for Self-ballasted lamps for general lighting services, Part: 2 Minimum Energy Performance Standards (MEPS) requirement sets maximum mercury content of 5 mg per CFL (AS/NZS, 2008). This proposed minimum energy performance standard may become regulation and implemented as part of the MEPS in November 2009. The current limit for mercury in fluorescent tubes in 15 mg per tube (AS/NZS, 2004).

United States

No U.S. standards for mercury content for CFLs specifically were found. The National Electrical Manufacturers Association (NEMA) has a voluntary programs for lighting manufacturers that limits the total mercury content of CFLs to 5 mg (less than 25 watts) or 6 mg (25 to 40 watts) (NEMA, 2008). The U.S. Environmental Protection Agency (EPA) requires all CFLs labeled as Energy Star to contain less than 5 mg mercury (Energy Star, 2008).

Europe

In Europe the mercury content of fluorescent lamps is controlled by the European Directive Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Regulations, or ROHs (ROHs, 2008). The ROHs limit for CFLs is 5 mg per lamp. The limits for fluorescent tubes are 10 mg for halophosphate lamps, 5 mg for triphosphate lamps with a normal lifetime and 8 mg for triphosphate lamps with a long lifetime (ROHs, 2008).

Toxicity of Mercury

Mercury is a metallic element that exists in one of three forms: metallic or elemental mercury (Hg^0), inorganic mercury (Hg^+ and Hg^{2+}salts) and organic mercury (e.g. methyl mercury, phenyl mercury). Elemental mercury is a silvery liquid that can vaporize at room temperature due to its low vapor pressure (WHO, 2003). The toxicology of organic mercury compounds is not discussed in this report as organic mercury compounds are not known to be present in fluorescent lamps.

When a CFL is broken, people will potentially be exposed to elemental mercury including vapor and inorganic mercury compounds. People may not be aware that they are being exposed to mercury vapor as it is colorless and odorless. Inhalation of mercury vapor is the key exposure pathway as 80-97% of inhaled elemental mercury is absorbed into the body through the lungs. In comparison only 0.01% of ingested elemental mercury is absorbed and 2.6% absorbed by dermal exposure to elemental mercury vapor (WHO, 2003). Once in the body, because elemental mercury is lipid soluble, it can cross biological membranes including the blood-brain barrier and the placenta (HPA, 2006). Mercury is circulated throughout the body and can accumulate in the brain and the kidneys causing changes to neurological and renal function. The absorbed elemental mercury is oxidized to $Hg^{2+}$and is excreted in the urine (WHO, 2003). Mercury vapor

has a half-life in the body of two months (Risher et al., 2003). Dermal exposure to mercury vapor can cause contact dermatitis (WHO, 2003).

The central nervous system is the most sensitive target for exposure to mercury vapor. Exposure to mercury can cause neurological and behavioral disorders in humans (WHO, 2003). Adverse effects to the central nervous system may be associated with chronic low exposures to mercury vapor (WHO, 2003). The majority of the available human data are from occupational studies in which the NOAELs (no observable adverse effect levels) were not identified.

The main exposure pathways for inorganic mercury compounds released following a lamp breakage are likely to be ingestion and/or inhalation of dust. However inorganic mercury compounds can be absorbed through the skin. Inorganic mercury compounds are caustic and can damage intestinal mucosal barriers if ingested. Exposure to inorganic mercury compounds can cause kidney damage (WHO, 2003).

The health effects associated with exposure to mercury depend on the magnitude of the exposure, the exposure duration, and the age and health status of the individual as well as the chemical species of mercury (i.e. elemental versus inorganic mercury) (Risher and DeRosa, 2007). Humans vary in their individual susceptibility to mercury exposure (WHO, 2003). ATSDR (1999) summarized potential effects from various levels of exposure to mercury. They report that no effects were reported from low-level exposures ranging from 21-39 µg/L in urine; however this does not preclude toxicity in sensitive populations. Medium-level exposure resulted in urine mercury levels of 40-60 µg/L and effects seen included acrodynia, fever, insomnia, rapidly shifting moods and tremors. High-level exposure resulted in urine mercury levels above 60 µg/L and effects seen included acrodynia, insomnia, possible respiratory effects, rapidly shifting moods, restlessness and tremors.

Sensitive populations

Populations sensitive to mercury exposure include infants, pregnant women, children under the age of 6 and people with kidney disease (ATSDR, 1999). Children and fetuses may be more vulnerable to adverse effects of mercury exposure particularly if the exposure occurs during a critical period of central nervous system development (Goldman et al., 2001). Dose response assessment risk values used in this report are designed to account for these sensitive individuals. Young children may also have a higher exposure to mercury vapor than adults as they have a breathing zone closer to floor where heavy mercury vapor is likely to accumulate (Counter and Buchanan, 2004). Exposure scenarios listed later in this report take this higher exposure into account.

Numerous examples exist of toxicity to children from greater sensitivity, greater exposure, or a combination of both. For example, Tunnessen et al. (1987) reported on a 23-month old child suffering from acrodynia resulting from exposure to elemental mercury. The exposure was from a carton of 8-foot fluorescent bulbs (mercury content not specified) that had broken in a potting shed adjacent to the child's house. The broken glass was cleaned up and discarded, but no other clean-up steps were taken. The child often used the potting shed as a play area.

Screening Exposure Assessment

Fate of mercury when a fluorescent lamp is broken

Mercury is not released from CFL sunless the lamp is broken. Once a CFL has been broken, mercury vapor, liquid mercury (if present) and mercury adsorbed onto the phosphor powder will be released (NJ MTF, 2002). It is unlikely that any spilled liquid mercury will be visible as the volume of mercury is small and any spilled mercury would form minute droplets on impact. The phosphor powder can separate from the glass when the lamp is broken (NJ MTF, 2002). The amount of mercury released as mercury vapor or associated with the phosphor powder will depend on the age of the lamp.

Fluorescent lamps will contain several species of mercury and the species present will depend on the species of the mercury added by manufacture and the age of the lamp (UNEP, 2005). Over time elemental mercury in the lamp will be oxidized and will form inorganic mercury compounds (predominantly HgO) (Aucott et al., 2003) and will partition to lamp components including the glass and phosphor powder (Jang et al., 2005). New lamps will release more mercury vapor whereas in older or spent lamps the mercury will have been oxidized and or have partitioned to lamp components. There is an initial spike in air-borne mercury concentration following breakage of a CFL or linear fluorescent tube as mercury vapor is released (Aucott et al., 2003; Johnson et al., 2008; Stahler et al., 2008) followed by slower release of mercury present in solid and liquid forms (amalgams, liquid elemental mercury, inorganic mercury and mercury absorbed onto lamp components).

Two recent studies quantified the amount of mercury released when a CFL is broken. Johnson et al. (2008) broke used and new CFLs in a 2 L Teflon container and measured the concentration of mercury vapor released over time. Two CFLs were used in the study – a 13 W lamp containing 4.5 mg of mercury and a 9 W lamp containing 5.0 mg of mercury. There was an initial high rate of mercury vapor release, which declined over 24 hours. Over the first hour the lamps released 12 to 43 µg of mercury vapor (1% or less). During the first 24 hours the 13 W lamp released 504 µg or 11.1% of the total amount of mercury, and the 9 W lamp released 113 µg or 1.9% of the total amount of mercury (total mercury in the lamp specified by the manufacturer). The broken lamps continued to release mercury for at least four days (the authors did not present extended data in the publication). Over four days the 13 W lamp released 1.34 mg or 30% of the total amount of mercury in the lamp. Spent (used) lamps released less mercury than new lamps. The rate of release of mercury from the broken CFLs was greater than from a drop of liquid mercury equivalent to the amount of mercury present in the CFLs. This increased rate of release was attributed to the larger surface area of mercury adsorbed onto the phosphor and lamp components in CFLs compared to the drop of liquid mercury. The study also found that removing the glass shards following a break on carpet reduced the discharge of mercury by 67% with the remaining mercury discharge assumed to have originated from spilled phosphor powder (Johnson et al., 2008).

Aucott et al. (2003) measured the rate of release of mercury from spent 4-foot fluorescent tubes containing 4.4 or 4.7 mg mercury. The study authors assumed mercury content of 4.55 mg per tube for their experiment. The fluorescent tubes were broken inside a 32 gallon (146 L) plastic container and the concentration of mercury vapor inside the plastic container was monitored. The pattern of emission was similar to that observed by Johnson et al. (2008) for broken CFLs. Initially there was a rapid rate of release followed by a declining rate of release. Aucott et al. (2003) attributed the decline in release rate to two factors -a gradual release of less volatile forms of mercury and oxidation of mercury. The mercury release rate was dependent on temperature, which was expected because of the greater volatility of mercury at higher temperatures. The authors estimated that 17 to 40% of the mercury present in a fluorescent tube will volatilize over a 14-day period with one third of the mercury being volatilized during the first 8 hours. Aucott noted that the mercury releases from disposal and recycling of fluorescent bulbs estimated by others range widely from 1% to 80% (e.g., U.S. EPA model indicate 6%; an industry report estimated 1%; and another author estimated a range of 20-80%).

Aucott et al. (2003) note that their measurements may be underestimates due to: artificial gradients in the barrel from lack of mixing of air, mercury may have adsorbed to test materials, and the Jerome 411 analyzer used measures elemental mercury vapor only. While it is believed that most of the volatile mercury in the bulbs is elemental, other volatile mercury compounds and powders may be released.

Other authors (e.g., Raposo et al., 2003; Jang et al., 2005) investigated partitioning of mercury from spent fluorescent tubes. Elemental mercury vapor is introduced in lamp manufacture, but the mercury in spent fluorescent lamps is adsorbed primarily to the phosphorous matrix, and to a lesser extent to the glass and other lamp components. Jang et al. (2005) measured partitioning of mercury in the vapor phase, loose phosphor, lamp glass, and end caps of fluorescent tubes. They found that total mercury concentration varied significantly among lamps, and reports that 94% or more of mercury remains either as a component of phosphor powders attached to the glass tube or in the glass, with very little mercury in the vapor phase. They concluded that the elemental mercury vapor has been partitioned to other compartments through oxidative reactions with phosphor powder and penetration mechanisms.

Maine (USA) Department of Environment Study (Stahler et al., 2008)

The most comprehensive study of mercury exposure following breakage of a CFL to date was undertaken by the Maine Department of Environmental Protection (Stahler et al., 2008). The aim of the study was to inform guidance on appropriate clean-up procedures following breakage of CFL. The study investigated a range of scenarios including clean-up method, type of lamp and floor covering (hardwood, short nap carpet and shag pile carpet). For each scenario, a new CFL was broken on a painted mesh cloth with mesh size 3/8" (hardware cloth) placed over a piece of floor covering placed inside a cardboard box. The CFL was crushed with a hammer. The size of room used for the measurements was 39 m^3 and the single window was 30 inches (76.2 cm) x 38 inches (96.5 cm). The resulting mercury vapor concentrations were measured at one foot (0.3 m) and five feet (1.5 m) sampling heights directly above the breakage site using Lumex RA 915+ mercury analyzers. The five-foot sampling height was chosen to represent the breathing zone of adults and the one-foot sampling height to represent the breathing zone of infants and toddlers. The mercury vapor results were compared with the Maine Ambient Air Guideline (MAAG) of

300 ng/m^3 (Stahler et al., 2008), which is the same as the U.S. EPA (2008) reference concentration (RfC), and the time elapsed before levels were below the MAAG were recorded. Additional scenarios were tested to address potential clean-up concerns, including different bulb manufacturers and wattages, vacuuming during and after cleanup, delays before clean up, a hot bulb, and cracking but not breaking the bulb. The study also investigated contamination of vacuum cleaners and assessed appropriate containers for disposal of broken lamps.

For all tested scenarios there was an initial elevated mercury concentration, which decreased very quickly and then declined over time. Data from all the scenarios investigated indicate that it took up to about 130 minutes for the concentration of mercury to fall below the MAAG value of 300 ng/m^3 after removing the broken lamp and ventilating the room by opening the window. The concentrations of mercury measured above the breakage site varied depending on the sampling height (with the highest concentrations being measured at 1 foot), the brand and/or wattage of lamp, absence or presence of room ventilation, and the cleanup method. Results also varied for repeat testing of the same brand of lamp.

Exposure Pathways

People may be exposed to the mercury contained in a CFL if it is broken. As discussed above, breaking the CFL results in mercury vapor being released to the air and possibly mercury adsorbed to phosphor powder separating from the glass. The primary form of mercury will be elemental mercury in the vapor phase. Over time, the mercury adsorbed to the phosphor powder will vaporize also. The primary human exposure pathway will be inhalation of the elemental mercury vapor. There is some limited potential for dermal exposure to the powder if a person were to touch the powder directly. It is possible that children could crawl on the floor where a CFL has broken and remaining powder might be absorbed by the skin. Given the broken CFL involves glass, it is not likely that children would be allowed in the area of the broken CFL until after clean up.

Exposure Scenarios

This report considers two human exposure scenarios associated with the breaking of a CFL, and within each scenario, two exposure levels that reflect different breathing areas between adults and children. The first scenario considers a single CFL broken in a small room that has no ventilation and no clean-up is performed. The second scenario also considers a single CFL broken in a small room, but in the second scenario adequate clean-up has been carried out and there is adequate ventilation in the room. The second scenario discusses the situation of ongoing mercury release from carpeting following the clean up.

To evaluate human exposure for the two chosen scenarios, experimental data are preferred, especially when these data mimic the desired conditions closely, are well controlled, and are measured reliably. However, if the conditions of the experiment do not match the desired scenario as closely as one would like, limitations and uncertainties may exist. In such cases mathematical models are appealing as one can construct them to address parameters or measures that may not be possible in a real world experiment. Constructing models that account for the many parameters and considerations in this type of situation would take considerable time and effort, although a very simple model mathematical model can be constructed (see Appendix A).

Scenario 1 – No Clean-up and No Ventilation

For this report, we believe that the use of the experimental results from the Maine study (Stahler et al., 2008) is preferable to a simple mathematical model because the scenarios we are asked to address closely resemble the experimental data. The Maine study (Stahler et al., 2008) tested a no clean-up scenario similar to that requested for this report. In Scenario S1, a single CFL ("Brand A" 60 watt equivalent) was crushed on a painted mesh cloth with mesh size 3/8" (hardware cloth) placed over a piece of wood floor covering placed inside a cardboard box. The resulting mercury vapor concentrations were measured at one foot (0.3 m) and five feet (1.5 m) sampling heights directly above the breakage site using Lumex RA 915+ mercury analyzers. The lower measurement was chosen as it was in the expected breathing zone of an infant; the higher value was chosen as it was in the expected breathing zone of an adult. The window and door were closed and the ventilation system turned off. Three separate trials were run for this no clean up scenario. Appendix B contains a description of the clean up measures and types of flooring used for the various Maine scenarios that involved clean up of the broken CFL.

Stahler et al. (2008) identified the CFL manufacturers for the bulbs they used, but did not provide the total mercury content for the CFLs. Brand A (used in Scenarios S1 to S6) was a 60-watt equivalent bulb made by Phillips. Culver (2008) reports that Phillips CFLs sold in the United States have a mercury content of 1.23 to 2.7 mg/bulb.

The data in Tables 2 and 3 are highly relevant for the no clean up Scenario 1 of interest here.

Table 2. Individual Data for Scenario 1.

	Time before Cleanup Initiated(min)	**Maximum Concentration at 1 foot (ng/m^3)**	**Maximum Concentration at 5 foot (ng/m^3)**	**1 Hour Average at 1 foot (ng/m^3)**	**1 Hour Average at 5 foot (ng/m^3)**
Trial 1	60	8,533	176	269	133
Trial 2	60	34,954	962	319	254
Trial 3	60	23,244	499	624	120

Individual trial data for Maine Scenario S1 (unvented, "Brand A" 14w=60watts, no clean up) were extracted from Stahler et al. (2008). 1-hour averages represent the average mercury concentration (ng/m3) for the first hour.

Table 3. Averaged Data for Scenario 1.

	Ave of Max (ng/m^3)	RSD[a] of Max (ng/m^3)	15 min avg. (ng/m^3)	15 min RSD	30 min avg. (ng/m^3)	30 min RSD	1 hr avg. (ng/m^3)	1 hr RSD
5 feet	546	72.4	193	50	186	50	169	44
1 foot	22,244	59.5	775	29	572	36	404	48

a. RSD = Relative Standard Deviation is computed as follows: RSD = 100 X (Standard Deviation of Trial averages)/(Average of Trial averages)

Averages mercury concentration [with relative standard deviations (RSDs)] for the three trials of Maine Scenario S1 (unvented, "Brand A" 14wt, no clean up) (extracted from Stahler et al. (2008).

Points to note in the evaluation of Scenario 1 with these experimental data include:

- Mercury concentrations are higher the closer one is to the broken CFL; concentrations are not uniformly distributed in the room;
- This brand of CFL contained 1.23 to 2.7 mg of mercury; other bulbs might have greater or smaller levels;
- These CFLs were new bulbs and likely have greater mercury vapor available for immediate release versus spent bulbs;
- The flooring used in Scenario S1 was wood.

Based on the above considerations, the values from Tables 2 and 3 reasonably represent the expected conditions for Scenario 1 in a New Zealand home setting where a CFL is broken. Concentrations at one-foot and five-foot heights from Tables 2 and 3 are used later in the risk characterization.

Scenario 2 – Mercury emissions after clean-up

Scenario 2 represents a situation where a single CFL is broken, the debris removed, and the room ventilated. Potential emissions from any mercury that may remain are of interest. The results from the Maine study (Stahler et al., 2008) are useful for this scenario as well. Stahler et al. (2008) measured mercury emissions from a number of scenarios where the broken CFL was cleaned up and the room air monitored until mercury levels fell below 300 ng/m^3. Stahler et al. (2008) provides estimates of concentrations, as well as insights into ongoing concentrations levels after cleanup measures were taken. See Appendix B for information about the clean up measures used for each of the scenarios tested in the Maine study.

Table 4 summarizes the average concentrations for each of the original five Maine clean-up scenarios that all utilized the same type of "Brand A" CFL. Measured mercury levels at the one-foot height were consistently greater than those measured at the five-foot height.

Table 4. Data for Scenario 2 through 6.

Scenario (Intake)	Avg. of Max[a] (ng/m^3)	RSD of Max[b]	15 min avg. (ng/m^3)	15 min RSD	30 min avg. (ng/m^3)	30 min RSD	1 hr avg. (ng/m^3)	1 hr RSD
S2 (5-ft)	666	23.1	106	42	67	54	37	43
S2 (1-ft)	12,261	37.7	307	43	176	41	95	42
S3 (5-ft)	770	40.9	220	19	152	21	96	19
S3 (1-ft)	8,323	33.0	372	26	225	18	126	14
S4 (5-ft)	484	42.0	165	23	115	22	66	17
S4 (1-ft)	12,334	69.4	415	40	232	38	119	37
S5 (5-ft)	424	41.8	203	16	147	20	94	33
S5 (1-ft)	10,449	71.3	428	55	248	48	136	46
S6 (5-ft)	333	27.0	153	26	120	33	48	35
S6 (1-ft)	6,855	127.4	251	66	154	57	87	53
All (5-ft)	549	48.1	176	33.4	132	41.7	90	57.1
All (1-ft)	11,880	77.0	42.5	52.1	266	63.3	159	82.7

a RSD = Relative Standard Deviation is computed as follows: RSD = 100 X (Standard Deviation of Trial averages)/(Average of Trial averages)

b Three trials were run for all six scenarios. An additional trial was run for scenario 3. Two trials, S2T1 and S3T1 (one foot intake) did not include 1-hour average results due to shortened runs.

Average concentrations in ng/m3 [with relative standard deviations (RSDs)] for the three trials of Maine Scenario S2 to S6 (extracted from Stahler et al. (2008).

The experimental data from Johnson et al. (2008), Aucott et al. (2003) and others support the Stahler et al. (2008) results, that the initial concentrations decline very rapidly as the mercury vapor dissipates.

Points to note in the evaluation of Scenario 2 with these experimental data include:

- Mercury concentrations are higher the closer one is to the broken CFL; concentrations are not uniformly distributed in the room;
- This brand of CFL contained 1.23 – 2.7 mg/kg-day of mercury; other bulbs might have greater or smaller levels;
- These CFLs were new bulbs and likely have greater mercury vapor available for immediate release versus spent bulbs;
- Three types of flooring used – wood flooring, short pile carpet and shag carpet. See Appendix B for details on the type of flooring for each scenario. The results differ with the type of flooring.

The values from Stahler et al. (2008) scenarios S2 through S6 reasonably represent the expected conditions for scenario 2 in a home setting where a CFL is broken. One-foot and five-foot measurements from Table 4 are used in the risk characterization.

The Maine study evaluated four additional scenarios to test different brands and wattages of CFLs. Scenario SA used a Brand B, 26W (90W equivalent); Scenario SBT2 used a Brand C, 13 W (60W equivalent); Scenario SC used a Brand D, 14W (60W equivalent); and, Scenario SE used a Brand B, 26W (100W equivalent). Table 5 summarizes the results from these four scenarios in which the cleanup methods and flooring (wood) were the same as that used for the Maine scenario S2and the results from an additional run for scenario S2.

Specifically, Table 5lists the maximum and average mercury concentrations at one-foot and five-foot heights from the individual trials. Table 6 lists the average value for all the trials for each of these same scenarios.

Table 5. Comparison of individual trial data of four additional scenarios with different bulbs to the results of Scenario S2.

Bulb/Scenario	Trial	5 ft Max	5 ft 1-hour Average	1 ft Max	1 ft 1-hour Average
	1	745	108	10040	199
	2	765	26	9173	50
Brand A - 14w (S2)	3	489	29	17569	126
	1	1640	199	7410	185
Brand B - 26w (SA)	2	9893	815	61037	1398
Brand C - 13w (SB T2)	2	1139	155	9523	220
	1	7288	527	65094	1048
Brand C - 13w (SE)	2	4206	806	25399	738
	1	4257	424	27224	684
Brand D - 14w (SC)	2	5927	298	6164	310

All scenarios used wood flooring and the same cleanup methods. The wattages of the different brand bulbs are identified in the text. Data extracted from Stahler et al. (2008).

Table 6. Comparison of average concentrations for each of four additional scenarios with different bulbs, to the results of Scenario S2.

Average of Brands	5 ft Max Average	5 ft 1-hour Average	1 ft Max Average	1 ft 1-hour Average
Brand A - 14w (S2)	666	54	12,261	125
Brand B - 26w (SA)	5767	507	34,224	792
Brand C - 13w (SB T2)	1139	155	9523	220
Brand C - 13w (SE)	5747	667	45,247	893
Brand D - 14w (SC)	5092	361	16,694	497

All scenarios used wood flooring and the same cleanup methods. The wattages of the different brand bulbs are identified in the text. Data extracted from Stahler et al. (2008).

As before, points to note in this evaluation include:

- Mercury concentrations are higher the closer one is to the broken CFL; concentrations are not uniformly distributed in the room;
- Brand A contained 1.23 – 2.7 mg/kg-day of mercury; the mercury content for other brand bulbs was not available;

- These CFLs were new bulbs and likely have greater mercury vapor available for immediate release versus spent bulbs;
- Wood flooring was used in the scenarios comparing bulb types; a different flooring (e.g., carpet) may have different results (see, for example S3 – S6 results in Table 4);
- The clean up measures used in each of these scenarios was the same, allowing for comparison of the scenarios.

The original six study scenarios from the Maine report (Stahler et al., 2008)as summarized in Tables 3, 4 and 5, provide useful data to compare relative initial peak releases of mercury (as well as concentrations after 15 to 60 minutes) from the same brand and type of CFL using different clean up scenarios. However, as demonstrated above in Tables 5 and 6, different brand and wattage bulbs produced results, which varied by up to 9-fold.

Emissions Remaining in Carpeting

Measures to remove the glass and debris from a broken CFL eliminate much of the mercury from the room, as does ventilating the room to dissipate mercury vapor. Breakages on carpeting are not likely to be completely cleaned. Thus, some mercury will likely be left behind in the carpet. The only information in the experimental literature found that addresses this is the study by Johnson et al. (2008). Johnson notes that removing the glass shards following a break on carpet reduced the discharge of mercury by 67%. Those authors assumed the remaining mercury discharge originated from the spilled phosphor powder (Johnson et al., 2008).

Stahler et al. (2008) measured emissions from broken CFLs on carpeting after clean up. For example, Scenario S3, one of the original Maine study scenarios using Brand A CFL, found mercury concentrations measured at one-foot and five-foot heights fell below 10 ng/m^3 for all the trials in sixty minutes (when the trial measurements ended). Most of the trials final concentrations measured were closer to10 ng/m^3. Stahler et al. (2008) used the same type bulb and clean up for a long pile or "shag" rug. Results from Maine Scenario S4 were similar at the end of the first hour.

Over time, the finite amount of mercury remaining would volatilize and the available mercury will be continually depleted. Other brand bulbs produced different results.

Stahler et al. (2008) found that agitating the carpet by rubbing a hand or tool over the surface, and repeated vacuuming generated additional peaks in the mercury concentrations, but these peaks cannot be compared with those previously described in Tables 3, 4 and 5, because the former values are measured at 1 inch from the surface on which the bulb was broken.

Dose-Response Information

There are several agencies that have developed human health toxicity values for exposure to mercury. Table 7 lists the specific agencies and their respective values that are relevant to exposure to elemental mercury vapor. All health risk values have been developed to protect sensitive subpopulations, which in the case of mercury, is recognized to be the pregnant woman and her fetus, the infant, and the young child.

Table 7.Selected "safe" concentrations for various times from different organizations.

Agency	Type of Exposure	Value	Year	Species	Critical effect	NOAEL/LOAEL	Uncertainty Factor[b]	Principle Study
NAC	AEGL2[a] 10 min	3.1 mg/m^3 (3,100,000 ng/m^3)	2008	Rat	absence of lesions in pregnant rats	NOAEL of 4 mg/m^3 for 2 hours/day for 10 days	3 (3A, 1H)	Morgan et al. 2002
	AEGL2 30 min	2.1 mg/m^3 (2,100,000 ng/m^3)	2008	Rat	absence of lesions in pregnant rats	NOAEL of 4 mg/m^3 for 2 hours/day for 10 days	3 (3A, 1H)	Morgan et al. 2002
	AEGL2 60 min	1.7 mg/m^3 (1,700,000 ng/m^3)	2008	Rat	absence of lesions in pregnant rats	NOAEL of 4 mg/m^3 for 2 hours/day for 10 days	3 (3A, 1H)	Morgan et al. 2002
	AEGL2 4 hr	0.67 mg/m^3 (670,000 ng/m^3)	2008	Rat	absence of lesions in pregnant rats	NOAEL of 4 mg/m^3 for 2 hours/day for 10 days	3 (3A, 1H)	Morgan et al. 2002
	AEGL2 8 hr	0.33 mg/m^3 (330,000 ng/m^3)	2008	Rat	absence of lesions in pregnant rats	NOAEL of 4 mg/m^3 for 2 hours/day for 10 days	3 (3A, 1H)	Morgan et al. 2002
OEHHA	Acute REL (1-hour)	0.0018 mg/m^3 (1800 ng/m^3)	1999	Rat	CNS disturbances in offspring	LOAEL of 1.8 mg/m^3, NOAEL not observed	1000 (10L, 10A, 10H)	Danielsson et al. 1993
OEHHA	Chronic REL	0.00009 mg/m^3 (90 ng/m^3)	2005	Human	Impairment of neurobehavioral functions in humans	LOAEL 25 µg/m^3 (LOAELADJ = 9 µg/m^3) , NOAEL not observed	100 (10L, 10H)	Piikivi and Hanninen 1989; Fower at al. 1983; Piikivi and Tolonen 1989; Piikivi 1989; Ngim at al. 1992
ATSDR	chronic inhalation MRL	0.0002 mg/m^3 (200 ng/m^3)	1999	Human	nervous system; increased frequency of tremors	LOAEL = 0.026 mg/m^3	30 (3L, 1A, 10H)	Fower, 1983
U.S. EPA	RfC	0.0003 mg/m^3 (300 ng/m^3)	1997	Human	nervous system	LOAEL = 0.025 mg/m^3 ($LOAEL_{ADJ}$ = 0.009 mg/m^3)	30 (10H&L, 3D)	Fawer et al., 1983; Piikivi and Tolonen, 1989; Piikivi and Hanninen, 1989; Piikivi, 1989; Ngim et al., 1992; Liang et al., 1993
WHO	Chronic tolerable concentration	0.2 µg/m^3 (200 ng/m3)	2003	Human	central nervous system effects	LOAEL = 20 µg/m^3 ($LOAEL_{ADJ}$ = 4.8 µg/m^3)	30 (10H, 3L)	Ngim et al. (1992)

a. Note that AEGLs also incorporate a time adjustment. See appropriate NAC discussion in the text for details.
b. Uncertainty factors are used to account for extrapolation or uncertainty in several areas. "L" accounts for extrapolation from a LOAEL to a NOAEL; "H" accounts for inter-human variability; "A" accounts for extrapolation from experimental animals to humans; "D" is used to account for deficiencies in the available toxicity data.

National Advisory Committee (NAC), USA

Acute Exposure Guideline Levels (AEGLs) for Hazardous Substances are developed by a National Advisory Committee (NAC), which includes members from Federal Agencies, State governments, chemical industry, academia, and other organizations. AEGLs are developed for different durations of 10 minutes to 8 hours, and are defined as the threshold concentrations above which the general population, including susceptible individuals, could experience health effects of specified severities following a single airborne exposure. Three threshold toxicity levels have been established for each chemical reviewed under the AEGL process including:

- AEGL-1 is the airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.
- AEGL-2 is the airborne concentration (expressed as ppm or mg/m^3) 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-3 is the airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.

There were no AEGL-1 values developed due to mercury having no odor or warning properties. The AEGL-2 values were developed based on no fetal effects in rats exposed to mercury vapor up to 4 mg/m^3 for 2 hours/day for 10 days (Morgan et al., 2002). The AEGL-2 values are: 3.1 mg/m^3 for 10-minutes; 2.1 mg/m^3 for 30-minutes; 1.7 mg/m^3 for 1-hour; 0.67 mg/m^3 for 4-hours; and 0.33 mg/m^3 for 8-hours. The AEGL-3 values were based on an estimated lethality threshold in rats. This threshold was estimated based on no clinical signs in rats exposed to 26.7 mg/m^3 for 1 hour; extending the exposure for one more hour resulted in 20/32 deaths (Livardjani et al., 1991). The AEGL-3 values are: 16 mg/m^3 for 10-minutes; 11mg/m^3 for 30-minutes; 8.9 mg/m^3 for 1-hour; 2.2mg/m^3 for 4-hours; and 2.2mg/m^3 for 8-hours.

Office of Environmental Health Hazard Assessment (OEHHA), California, USA

The Office of Environmental Health Hazard Assessment (OEHHA) has derived a chronic reference exposure level (REL) of 90 ng/m^3 (OEHHA, 2005) and an acute REL of 1800 ng/m^3 for a one-hour average exposure to mercury vapor (OEHHA, 1999). Specifically, for the chronic REL, the nervous system is the target endpoint. The chronic REL was derived using data from occupational studies where male workers had been exposed to mercury vapor. A no observed adverse effect level (NOAEL) was not identified for these studies and the chronic lowest observed adverse effect level (LOAEL) was 25 $\mu g/m^3$ (time adjusted LOAEL is 9 $\mu g/m^3$). The chronic REL of 90 ng/m^3 was derived using the LOAEL value of 25 $\mu g/m^3$and a cumulative uncertainty factor of 100 (subchronic uncertainty factor of 1, LOAEL uncertainty factor of 10, interspecies uncertainty factor of 1, and an intra-species uncertainty factor of 10). The chronic REL is for exposure to mercury salts and elemental mercury (OEHHA, 2005).

The acute REL of 1800 ng/m^3 is based on a reproductive/developmental endpoint. Specifically, the critical effects were considered to be behavioral deficits following *in utero* exposure to metallic mercury vapor. The acute REL was derived using data from a study of pregnant rats (Danielsson et al., 1993) exposed to concentrations as low as 1.8 mg/$m^3$of mercury vapor for one hour per day or 3 hours per day during gestation. The LOAEL was 1.8 mg/$m^3$for central nervous system disturbances in the offspring. The extrapolated one-hour concentration was also 1.8 mg/m^3.The REL was derived using a cumulative uncertainty factor of 1000 (LOAEL uncertainty factor of 10, an interspecies uncertainty factor of 10 and an intra-species uncertainty factor of 10).

The OEHHA released draft revised reference exposure levels for mercury in November 2007 (OEHHA, 2007). The revised acute REL is 600 ng/m^3 and was modified from the previous value by increasing the cumulative uncertainty factor from 1000 to 3000. The chronic REL for mercury was revised to 30 ng/m^3 using a cumulative uncertainty factor of 300 (OEHHA, 2007). The cumulative uncertainty factor was calculated using a LOAEL uncertainty factor of 10, an interspecies uncertainty factor of 1 (toxicokinetic uncertainty factor of 1, toxicodynamic uncertainty factor of 1), an intra-species uncertainty factor of 30 derived from an toxicokinetic uncertainty factor of 3 (default for inter-individual kinetic variability) and a toxicodynamic factor of 10 (greater susceptibility of children and their developing nervous systems).Due to the use of an unconventional uncertainty factor for human variability, and because of their interim status, the draft OEHHA REL values (OEHHA, 2007) were not considered for use as benchmark health values for this report.

Agency for Toxic Substances and Disease Registry (ATSDR), USA

The Agency for Toxic Substances and Disease Registry (ATSDR) has derived a chronic inhalation minimal risk level (MRL) of 200 ng/m^3 for airborne mercury exposure and suggested this level as an action level for indoor air concentrations of mercury (ATSDR, 2000). An MRL is defined as a screening tool for public health officials to use when determining whether further evaluation of potential exposure at a hazardous waste site is warranted (ATSDR, 1999). An action level is defined as "an indoor air concentration of mercury vapor, which should prompt consideration of the need to implement a recommended response by public health and environmental officials". In setting the action levels the ATSDR assumed that the residentially exposed population includes pregnant women and children under the age of six years and the exposure is up to 24 hours per day, seven days per week for an extended time period of months to years (for children),that is, a worst case scenario (ATSDR, 2000).

A chronic MRL is a level of exposure at which adverse effects would not be expected to occur. It assumes an exposure of 24 hours per day for 30 years. The MRL of 200 ng/m^3 was derived from the same occupational study the EPA used to derive its RfC. The LOAEL from the Fower (1983) study of 26 µg/m^3 (ATSDR's value was arrived at by different rounding than EPA) was used and adjusted from the 15 years of occupational exposure (40 hours per week) to a continuous exposure of 168 hours per week (24 hours per day, 7 days per week). An uncertainty factor of 30 was used to account for using a LOAEL and differing sensitivities of individuals.

United States Environmental Protection Agency (U.S. EPA), USA

The U.S. EPA inhalation reference concentration (RfC) for chronic exposure to mercury vapor is 300 ng/m^3. An RfC is defined as "an estimate of a daily inhalation exposure of the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime." The RfC was calculated using a LOAEL derived from the same studies of adult occupational exposure to mercury vapor as those used to derive the OEHHA chronic REL (see above). The U.S. EPA used a lower uncertainty factor than OEHHA, but similar to that used by ATSDR. The combined uncertainty factor was 30. A factor of 10 was applied for protection of sensitive subpopulations and the use of a LOAEL, and an uncertainty factor of 3 was applied for lack of information and in particular a lack of developmental and reproductive studies (IRIS, 1995).

World Health Organization (WHO) and International Programme on Chemical Safety (IPCS)

Concise International Chemical Assessment Documents (CICADs) are the latest in a family of publications from the International Programme on Chemical Safety (IPCS) — a cooperative program of the World Health Organization (WHO), the International Labor Organization (ILO) and the United Nations Environment Program (UNEP). CICADs join the Environmental Health Criteria documents (EHCs) as authoritative documents on the risk assessment of chemicals. Several studies (Ngim et al., 1992)are in agreement that mild subclinical signs of central nervous system toxicity can be observed among people who have been exposed occupationally to elemental mercury at a concentration of 20 μg/m^3 or above for several years. Extrapolating this to continuous exposure and applying an overall uncertainty factor of 30 (10 for interindividual variation and 3 for extrapolation from a LOAEL, with slight effects to a NOAEL), a tolerable concentration of 0.2 μg/m^3 was derived.

Risk Characterization

Data from the various exposure scenarios (Stahler et al., 2008) were used in the comparison to selected human health toxicity benchmarks noted above. The human health toxicity benchmarks were selected based primarily on matching the appropriate exposure duration. For example, even though dose response assessment values of ATSDR, EPA and WHO are available for chronic exposure, these values were not used in this risk characterization because other dose response assessment values of more appropriate exposure duration (acute) were available. Each exposure scenario with appropriate comparison benchmarks are described below.

Scenario 1 – No Clean-up and No Ventilation

Scenario 1 is the "no clean-up" scenario. As discussed in the Exposure Section, the exposure data from scenario S1 reported in Stahler et al. (2008) were used, and specifically the mercury vapor concentrations measured at the one-foot (0.3 m) and five-foot (1.5 m) sampling heights directly above the CFL breakage site. Three separate trials were run for scenario S1. Concentrations at 15, 30 and 60 minutes are listed in Table 2 above. The maximum concentrations occurred within seconds of the CFL breakage. Data for 1-hour average values are listed in Table 3. Please note the use of log scales for the y-axes in these and other Figures.

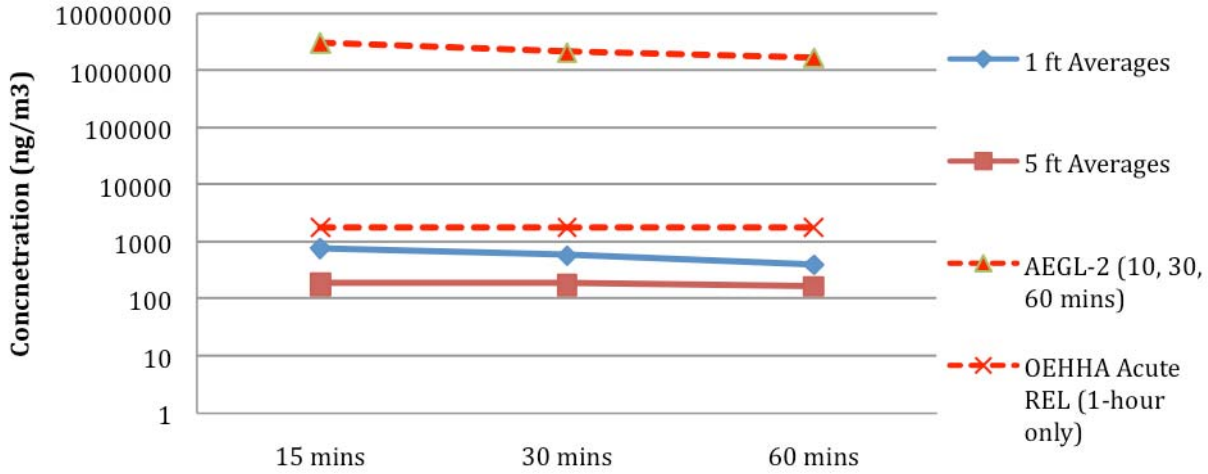

Figure 1. Average mercury vapor concentrations at 1ft and 5 ft from floor for 3 different exposure durations after breakage.

Figure 1 shows the average mercury vapor concentrations from the Maine study Scenario S1 (Stahler et al., 2008) at one-foot and five-foot heights from the floor, for 3 different exposure durations (see Table 3).None of the average concentrations exceed the AEGL-2s (10, 30, or 60 min at 3.1 mg/m^3, 2.1 mg/m^3, and 1.7 mg/m^3 respectively) or the one-hour average exposure OEHHA acute REL (1-hour at 1800 ng/m^3). The one-foot average concentrations exceed the 300 ng/m^3 level that represents one estimate of a "safe" level for a lifetime of exposure (in this case EPA's RfC) (not shown in Figure 1). The average one-foot concentration declines more rapidly than the five-foot measurements.

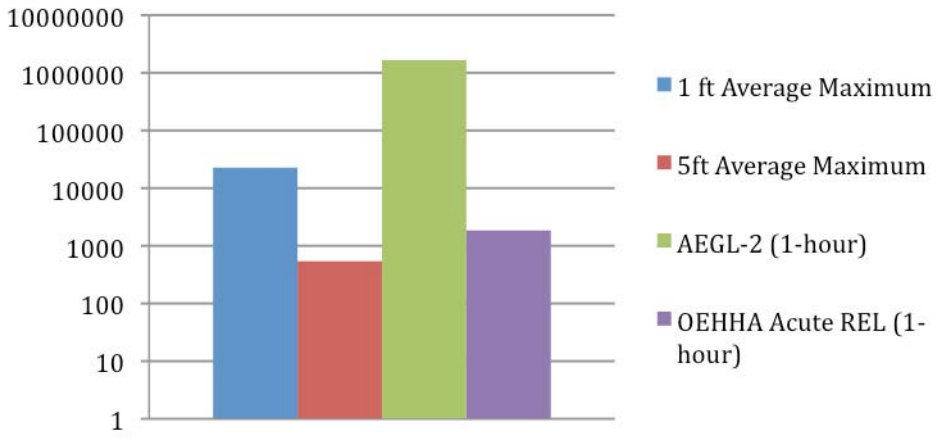

Figure 2. The maximum mercury vapor concentrations at 1ft and 5 ft from floor (average of three trials).

Figure 2 illustrates how the averaged maximum mercury vapor concentrations from the Maine study Scenario S1 (Stahler et al., 2008; and shown here in Table 3), taken at one-foot and five-foot heights from the floor, compare with short term toxicity values (see Table 4). The one-foot average maximum concentration exceeds the one-hour average exposure OEHHA acute REL (1-hour at 1800 ng/m^3), but does not exceed the AEGL-2 1-hour value (1.7 mg/m^3). However, the highest one-hour average concentration at 1 foot was 624 ng/m^3 (see Table 2), well below the OEHHA acute REL of 1800 ng/m^3. In all the trials, these maximum values rapidly declined, with the 15-minute average concentrations well below 1000 ng/m^3 for both heights. Other investigators (e.g., Johnson et al., 2008; Aucott et al., 2003) also measured high peak concentrations that rapidly declined to much lower levels in a matter of seconds or minutes. The average maximum concentrations at the five-foot height for this no clean up scenario exceeded several of the agency "safe" exposure values listed in Table 7 after chronic exposures.

The experimental data from Johnson et al. (2008), Aucott et al. (2003) and others support the Stahler et al. (2008) results that the initial concentrations decline very rapidly as the mercury vapor dissipates.

Scenario 2

The mercury concentration data reported in Stahler et al. (2008) were also used for Scenario 2. Mercury vapor concentrations were measured continuously until concentrations fell below 300 ng/m^3, or at least one hour after the initial CFL breakage. Air was continuously sampled at one-foot (0.3 m) and five-foot (1.5 m) heights directly above the CFL breakage site. Scenarios S2-S6 are appropriate to use for our Scenario 2 here. All five of these scenarios used the exact same brand and wattage (Brand A, 14w) CFL and initial clean up measures. Each scenario had a window open. Three types of flooring were used (wood, short nap, and long pile carpet). Two of these scenarios (S5 and S6) also included vacuuming as part of the clean-up procedure. Details on the different scenarios are found in Appendix B. Figure 3 displays the maximum concentration (average of three trials for each scenario) and the average 1-hour concentrations for scenarios S2 through S6 from the Maine study. These concentrations are compared with the

one-hour average exposure OEHHA acute REL (1-hour at 1800 ng/m^3) and theAEGL-2 1-hour value (1.7 mg/m^3).

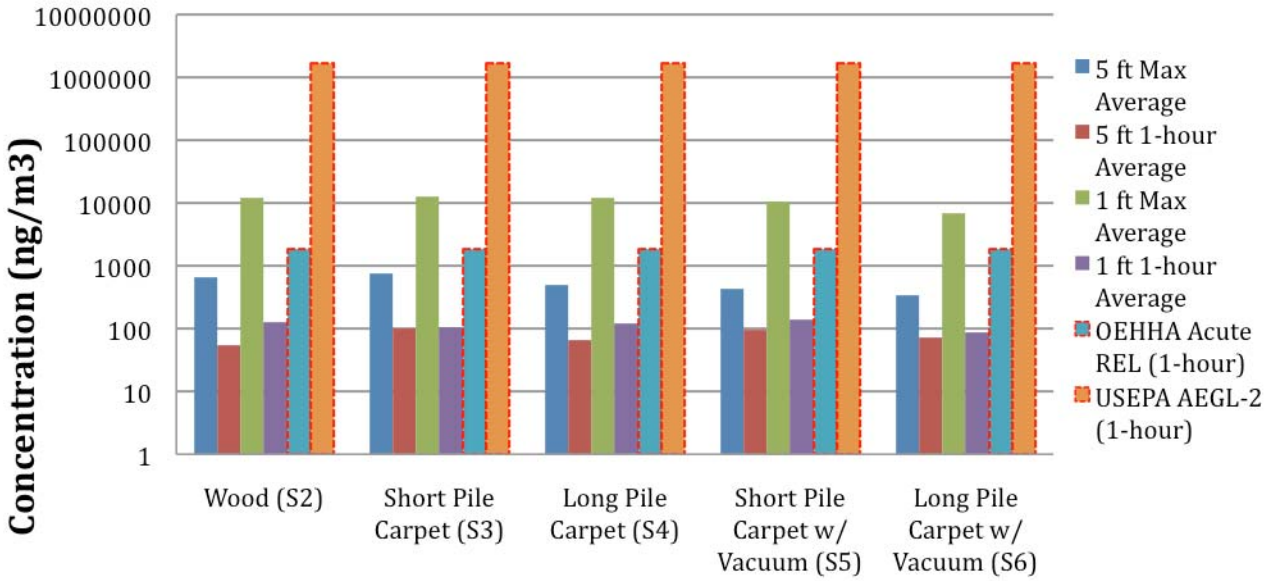

Figure 3. Maximum and 1-hour average concentrations for Scenarios 2-6 compared with the short term values of OEHHA and the U.S. AEGL.

The results for these five scenarios are remarkably similar even with the use of different types of flooring and the addition of vacuuming to the clean up. Only the averaged one-foot maximum concentrations exceed the one-hour average exposure OEHHA acute REL (1-hour at 1800 ng/m^3) and the 300 ng/m3 level that represents a "safe" level for a lifetime of exposure, but none of them exceeds the AEGL-2 1-hour value (1.7 mg/m^3). No other average concentrations exceeded either "safe" value. Note that the one-hour average concentrations at one-foot all fell below, and sometimes far below, the one-hour average exposure OEHHA 1-hour REL of 1800 ng/m^3. In all of these scenarios, these maximum values rapidly declined, with all but the 15-minute average concentrations below 500 ng/m^3 for either height.

Figures 4 and 5 show the variation in mercury vapor released across a variety CFL brands with varying wattages. For each of these scenarios, the same clean up method was used as scenario S2 (wood flooring) and only the type of bulb was varied (see Tables 5 and 6 for data).

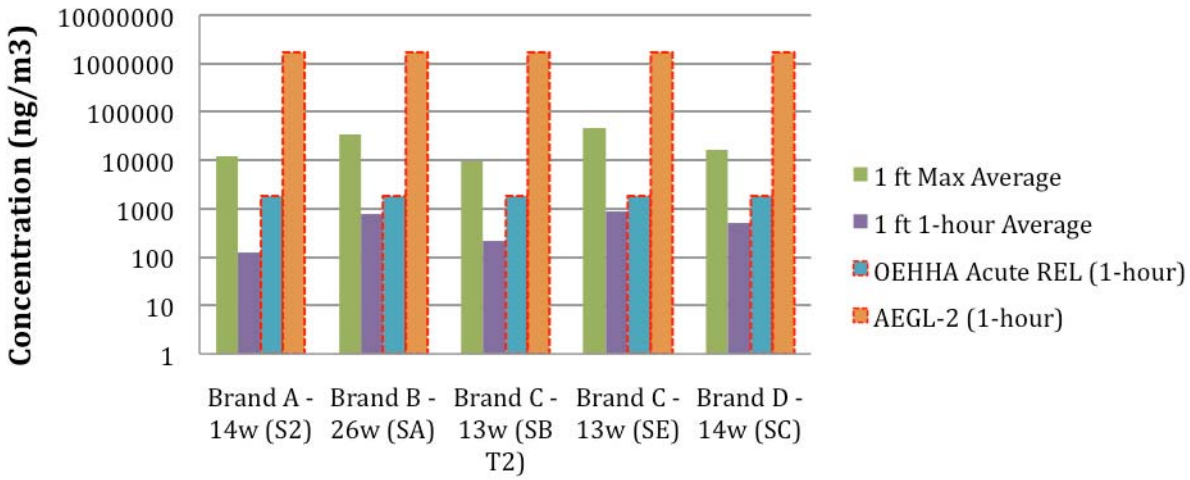

Figure 4. Comparison of maximum and 1-hour average mercury concentrations at one foot from scenarios that tested a variety of CFL Brands and Wattages.

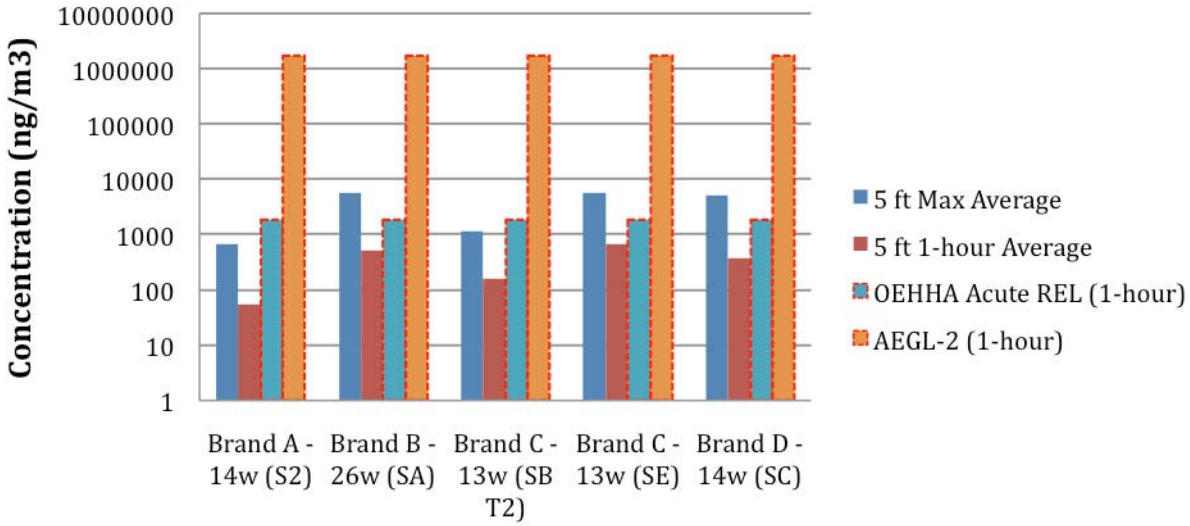

Figure 5. Comparison of maximum and 1-hour average mercury concentrations at five feet from scenarios that tested a variety of CFL Brands and Wattages.

As one would expect, the one-foot concentrations were greater than concentrations measured at the five–foot height (compare Figure 4 to Figure 5). The one-foot maximum concentration (average of all trials within the scenario) exceeds the one-hour average exposure OEHHA acute REL (1-hour at 1800 ng/m^3) for all the scenarios. However, the results here are similar to other scenarios, in that the maximum concentrations may have exceeded the one-hour average exposure OEHHA REL, but the one-hour average concentrations were all below this benchmark value, which is designed to protect humans from adverse effects from one-hour exposures. Neither the maximum values, nor the average concentrations exceeded the AEGL-2 1-hour value of 1.7 mg/m^3. Only a slight variation is seen between brands with the same wattage CFL, however the 13W and 26WCFLs appear to release higher mercury concentrations when broken than the 14WCFLs.

Stahler et al. (2008) utilized additional scenarios with larger wattage bulbs and repeated vacuuming over a seven-day period. The results from this scenario would be representative of what mercury emissions from carpeting might occur after an adequate clean up. Figures 6 and 7 show the mercury concentrations from a larger, 26W, CFL broken on a short pile carpet with no room ventilation on the initial day of clean-up and with vacuuming 4, 5 and 6 days after initial clean-ups. For the final vacuuming (7 days after initial clean-up), the room was ventilated. Figure 6 shows concentration at the five-foot height and Figure 7 shows concentrations at the one-foot height. See Appendix D for the data used for Figures 6 and 7 (extracted from Stahler et al., 2008 Appendix A).

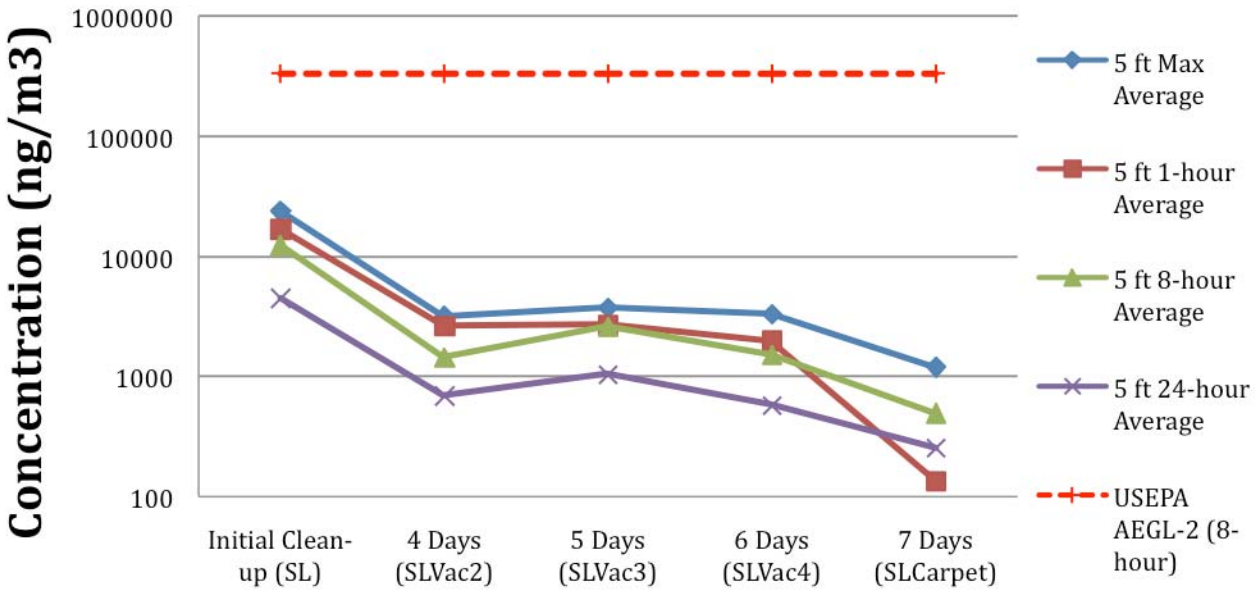

Figure 6. Mercury concentrations at 5 feet from a scenario (SL) with multiple vacuuming sessions over a seven-day period.

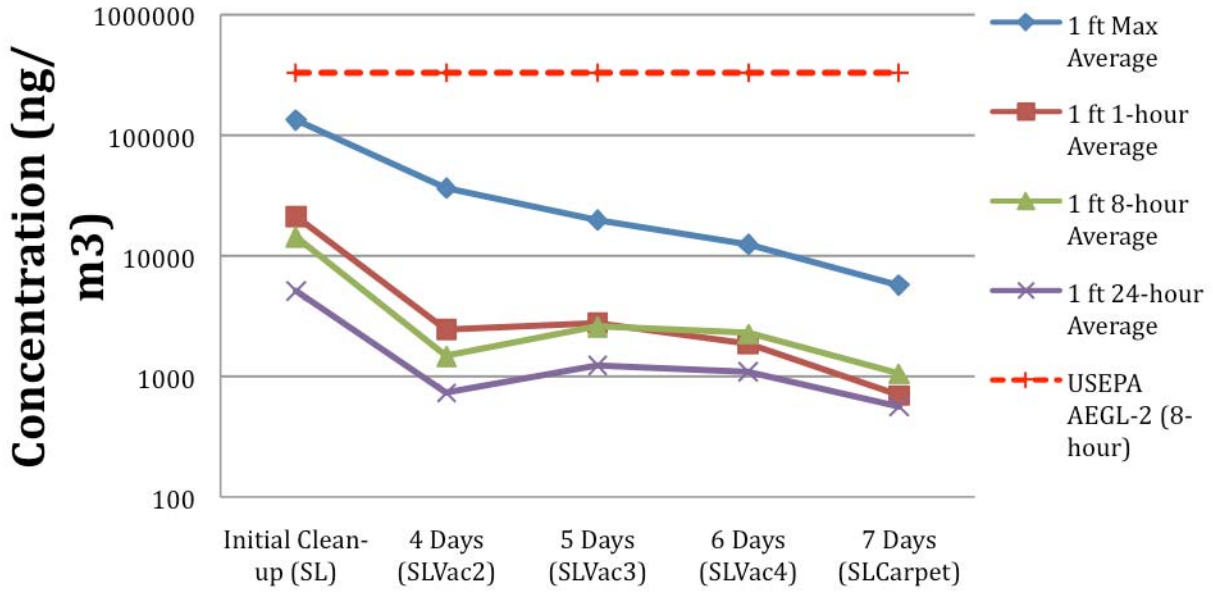

Figure 7. Mercury concentrations at 1 foot from a scenario (SL) with multiple vacuuming sessions over a seven-day period.

For this scenario, involving repeated vacuuming and a higher wattage bulb, none of the maximum or one-hour average concentrations exceeded the AEGL2 8-hour value of 0.33 mg/m^3. However, several of the concentrations exceed the one-hour average exposure OEHHA Acute REL (1-hour) of 1800 ng/m^3. These data demonstrate that repeated vacuuming over several days decreases the mercury concentrations at both measured heights, but that exposures in excess of the 1 hour REL are possible, and even likely. Decreases were enhanced on Day 6 and Day 7, when ventilation was added to the final day of vacuuming.

Hazard Quotients

To evaluate the safety of a particular exposure level to a non-carcinogenic hazard, the hazard quotient or hazard index concept is generally used. The hazard quotient is typically developed for one chemical and one exposure; the hazard index is typically developed for multiple chemicals and/or multiple exposures. In either case, the quotient or index is computed by dividing the exposure estimate by a risk value corresponding to the duration of exposure. In this screening level risk characterization, we develop hazard quotients using averaged-maximum and averaged one-hour exposures and dividing these averaged exposures by conservative health risk values. Table 8 shows hazard quotients for Scenario 1, which compares averaged concentrations found in Table 3 and selected risk values. Risk values were selected primarily to match the exposure duration of interest. Other choices may be reasonable, such as lifetime health risk values, but such choices would need sufficient justification.

A hazard quotient greater than 1 suggests the need to examine exposure scenario more closely as the exposure is approaching the "safe" dose. For the no clean up, Scenario 1, all hazard quotients were less than one (see Table 7), some well below 1. This demonstrates that even

without adequate ventilation (an open window in the case of Scenario 2), the averaged one-hour concentrations are not likely to be a health risk, even if the broken bulb was not cleaned up immediately.

Using concentrations appropriate for Scenario 2 (summarized in Table 4), hazard quotients are approximately equal or less than those calculated for Scenario 1. This indicates that adequate ventilation and clean up results in lower mercury concentrations, and like results from Scenario 1, human health risk is unlikely.

A likely "no risk" statement is also possible based on the hazard quotients from various types of bulbs, because even though some bulbs yield up to 9-fold higher mercury releases, the corresponding hazard quotients would still be less than 1 (see Table 6 for exposure information).

Table 8. Hazard Quotient for Scenario 1.

Agency Risk Value	Agency Value (ng/m^3)	Avg. of1 ft Max	1ft 1 hr Avg	Avg. of5ft Max	5ft 1hr Avg
AEGL-2 (10 minutes)	3,100,000	<0.01	NA	<0.01	NA
AEGL-2 (30 minutes)	2,100,000	0.01	NA	<0.01	NA
AEGL-2 (1-hour)	1,700,000	NA	<0.01	NA	<0.01
OEHHA Acute REL OEHHA (1-hour)	1800	NA	0.2	NA	0.09

a. Hazard Quotient = Exposure estimate (or measurement) / Appropriate risk value. Values greater than 1 call for additional investigation. Exposure data found in Table 3. NA = Not applicable

Conclusion

This screening assessment concludes that inorganic mercury vapor is the mercury form of concern from CFL breakage, and that releases of this mercury vapor vary within reasonably narrow bounds based on age, size and manufacturer of the bulb. Investigators have studied or measured the release of mercury vapor from CFL bulb breakage scenarios. Several of these scenarios closely match those of interest to the government of New Zealand as outlined above. A review of the data on mercury releases from these studies, along with conservative and length-of-exposure matching health risk benchmark values indicates that few situations with breakage of CFLs will result in releases that are at levels that may likely generate a health concern, but that some cleanup scenarios results in exposure estimates that exceed some risk characterization targets and should be further studied. Uncertainties in this conclusion are briefly discussed.

General Uncertainties

Several general areas of uncertainty are evident in this preliminary screening risk characterization. Specifically, since actual test data have been used in this risk characterization, uncertainties include:

- Mercury concentrations are higher the closer one is to the broken CFL, concentrations are not uniformly distributed in the room, and measurements at one-foot and five–foot heights may underestimate the occasional higher concentration elsewhere;
- The brands of CFL tested contained generally from 1 to 3mg of mercury, other bulbs might have greater or smaller levels of mercury;
- These tested CFLs were new bulbs and likely have greater mercury vapor available for immediate release versus spent bulbs;
- Stahler et al. (2008) illustrated that variability exists between trials within a scenario and between scenarios. This variability was not so great, however, as to affect the overall results.

Real life conditions will likely vary in some or many ways from the experimental design used to develop these data. For example, the room size used in the Stahler et al. (2008) was 39 m^3, which is larger than the 22.5 m^3 size recommended by New Zealand. However, this approximately 40% smaller room size for New Zealand will not affect the overall results, that is, this reduction only results in an increase in the maximum hazard quotient to about 0.5, which is still less than the target no-action value of 1.

Other uncertainties, such as room temperature, Stahler et al. (2008)'s use of cold bulbs and intense vacuuming, and type of floor covering are likely to result in little change to the hazard quotients discussed above. For example, the room temperature in the Stahler et al. (2008) study varied from 17.2°C to 27.7° C. The authors determined that correcting temperature for 23° C (73°F) would not significantly affect the study conclusions. However, they also concluded that if the study had been conducted at 90° F (32°C), the mercury concentrations would have been about 2-fold higher. This increase, while likely to happen at higher temperatures, only marginally affects the hazard quotients found in Table 8. Aucott et al. (2005) also determined that concentration increased with temperature, presumably because warmer room temperatures will result in faster evaporation of mercury.

Stahler et al. (2008) found that breaking one bulb on wood, short pile or shag carpet results in almost immediate high mercury concentrations, but if a window is opened and the broken lamp cleaned up, the concentrations fall below 300 ng/m^3 in 10 minutes or less (for the initial scenarios tested). It also appears that variations in exposure levels are primarily due to wattage. Brand A was used for the 6 original scenarios and it has lowest average concentrations (except brand F, which is also a low wattage bulb), but other brands with higher wattages generally resulted in greater concentrations at 15, 30 and 60 minutes. Insufficient data also exist on the exposure scenario due to spent bulbs. There is data that show spent bulbs release less mercury than new bulbs, which is the reason why exposure scenarios were limited to new bulbs as they represent the worst case scenario. Spent bulbs are not likely to be of health risk when compared to the risk from new bulbs.

Perhaps the largest uncertainty in this risk characterization, however, is in the choice of the dose response assessment value used in the development of the hazard quotients. Our choices of AEGLs of various durations for comparison with the averaged maximum one-foot and five-foot exposures, and of the established 1-hour average exposure REL from OEHHA for comparison with the average 1-hour exposures seem reasonable because:

- The AEGLs and California REL are well developed and have been through an external peer review. Both sets of risk values purport to protect sensitive individuals, including children;
- A properly developed hazard quotient closely matches lengths of exposures in both the exposure and dose response assessments. For example, it is generally not appropriate to match a one-hour exposure with a "safe" concentration for lifetime exposure, if a shorter-term value, which protects sensitive individuals, is available;

However, the California RELs are now being revised, with the possibility that lower values may be adopted in the near future. Moreover, a large disparity exists between the 1-hour AEGL2 of 1,700,000 ng/m^3 and the 1-hour REL of 1800 ng/m^3 (~900 fold). Additional investigation of this disparity should be considered a high priority. Finally, alternative dose response assessment values might be contemplated, if the existing choices for the appropriate exposure duration of concern have irresolvable issues. For example, choices such as the EPA RfC, the ATSDR MRL or the WHO TC, are possible, but if considered, some allowance for differences in exposure duration would be needed.

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Appendix A – Simplistic Exposure Model

To estimate exposure of humans to mercury from broken CFLs) one could construct a model to illustrate mercury emissions. Upon receiving this assignment TERA subcontracted to EQM (Fred Hall and John Kominsky) to construct a simple mathematical model to estimate the concentration of mercury over time within a small room. They assumed a fraction of the mercury is released immediately on breakage of the CFL and the remainder evaporates into the room over a period of time. In the short time available, a simple mathematical model is all that could be developed. We realized that a simple model would have difficulty predicting actual exposure concentrations given the complexity of the exposure situations. A number of investigations of emissions from broken CFLs and other fluorescent lights (e.g., Johnson et al., 2008; Aucott et al., 2003) and the work by Stahler et al. (2008) demonstrate the wide range of variability of results and number of variables found in real life situations. We present the model and some initial results here.

Overall the simple model shows that the concentration of mercury (Hg) peaks shortly after the CFL breaks and decreases gradually over time as the Hg remaining behind evaporates. The model assumes that upon breaking a CFL, a portion of Hg from the CFL is released into the room and is immediately dispersed. It is also assumed that the remaining mercury is in liquid form and the evaporation rate is calculated using the vapor pressure of liquid Hg at room temperature.

The model predicts that the immediate dispersion of gaseous Hg results in an initial peak concentration of several thousand nanograms per cubic meter. Over time, the Hg not immediately released into the room gradually evaporates in a manner proportional to the exposed surface area of the Hg. As the initial Hg release dissipates, the model shows that the evaporation of the Hg, the mixing of the Hg vapor in the room air, and room ventilation result in much lower concentrations of Hg. As the surface area of the Hg is reduced over time due to evaporation, the model predicts that the concentration in the room also decreases (assuming constant air flow through the room) until the Hg is totally evaporated.

This simple box model uses a small number of variables and makes some simplifying assumptions to provide an estimate of the concentration that would result from breakage of a single CFL in a room.

Simplifying assumptions:

- A portion of the mercury is totally sublimed (is in vapor phase) upon breakage of the bulb and that the mercury vapor will reach equilibrium in the room immediately;
- Concentration is at equilibrium, no part of the room has higher or lower concentrations.

Initially, there is no ventilation in the room, so no mercury escapes (providing the peak concentration). A typical ventilation rate for a room with closed door and window is then added.

The model also uses the following values for elemental mercury:

Molecular Weight Hg =	**200.6**		
Density Hg =	**13.5**	**g/cm^3**	
Vapor Pressure Hg =	**0.0018**	**mm**	at 298 °K
Hg equilibrium in air =	**0.0000024**	**Mole fraction at atmospheric pressure**	
Hg equilibrium in air =	**2.4**	**ppm**	

Equation 1 calculates the equilibrium concentration of mercury using the following equation:

Equation 1.

$$P^{Hg} = \frac{P^{vap}}{P^{atm}}$$

Where:

P^{Hg} = equilibrium concentration of Hg (mole fraction)

P^{vap}= vapor pressure of Hg

P^{atm} = atmospheric pressure

The model allows the user for vary several key parameters:

- the amount of mercury in the CFL;
- the percentage of mercury immediately released;
- the box dimensions.

Using these simplifying assumptions and an air tight room, one would simply divide the total mercury by the volume of the room for an equilibrium concentration.

However, rooms in homes are not totally sealed and the model provides for some air flow and mixing within the room. The model allows the user to input the following:

- air velocity in the room;
- air flow through the room;
- a mixing factor.

With the introduction of air flow resulting in some air leaving the room, we can then model mercury concentration over time with Equation 2:

Equation 2. $$C = C_i e^{\frac{-\Delta t Q_{in}}{kV}}$$

Where:	C =	Concentration at time t
	C_i =	Initial concentration
	t =	time
	k =	Mixing factor
	Q_{in}=	Ventilation rate
	V =	Volume of room or imaginary box

The mixing factor (k) is 1 for perfect mixing and generally 2 to 10 for practical situations (10 results in the highest concentrations).

Using the model one could vary the parameter values and see how the concentration changes. For example, to consider a child who is low to the ground, a worst case assumption that all the mercury is lower to the floor could be made and the height of the box could be shortened. If one opened a window or door, the air flow would increase and the concentrations would reduce more quickly.

Ongoing Mercury Release

Sheet 2 of the Excel file models ongoing evaporation of remaining mercury after clean up using the Equation 3:

Equation 3. $$Q_m = \frac{MKAP^{sat}}{R_g T_L}$$

Q_m =	evolution rate of volatile material, ng/minute
M =	molecular weight of Hg
K =	mass transfer coefficient
A =	area of exposure Assume number of spheres of liquid Hg to calculate surface area
P^{sat}	saturation pressure of Hg
R_g	ideal gas constant
T_L	temperature of the liquid

The user can enter the total mercury in the CFL, the fraction remaining after clean up, and the density of the mercury in the table below. The model will calculate the surface area of the remaining mercury with time.

Time, min	Hg in CFL, mg	Fraction Remaining After Clean Up	Hg Density, gm/cm^3	Hg Remaining, mg	No. of Spheres	Volume of Each Sphere, cm^3	Radius of Each Sphere, cm	Surface Area for all Hg, cm^2
0	5.0	0.67	13.50	3.35	1	0.000248	0.0390	0.0191
5			13.50	3.30	1	0.000245	0.0388	0.0189
10			13.50	3.26	1	0.000241	0.0386	0.0187
15			13.50	3.21	1	0.000238	0.0384	0.0186

Then mercury concentration as a unit of time is calculated and plotted. The mixing factor is entered by the user. The model assumes a constant evaporation rate even though it will become less over time due to decreasing surface area. For mercury concentration as a unit of time, Equation 4 (from, "Calculation Methods for Industrial Hygiene") is used.

Equation 4.

$$C_2 = \frac{GK}{Q_{in}} - \frac{K}{Q_{in}}\left(G - \frac{Q_{in}C_1}{K}\right)e^{-\frac{Q_{in}}{KV}(t_2 - t_1)}$$

C_2 is Airborne concentration at time equal 1

C_1 is Airborne concentration at time equal 2

G is Generation rate of contaminant

Q_{in} is rate of ventilation into the room or imaginary box

K is the mixing factor, which may vary from 1 to 10 (1 is perfect mixing, 10 is poor mixing)

V is volume of the room or space

t_1 is time 1

t_2 is time 2

The model predicts the Hg concentration in a room after breaking a CFL. The major variables are the amount of gaseous mercury immediately released into the air, the evaporation properties of the Hg remaining, the room ventilation, and the mixing efficiency of the gaseous Hg within the room (this is estimated by applying the mixing factor described above). The results shown above assume that a significant portion of the Hg is released as a gas (a third or greater); the remaining Hg evaporates following the properties of liquid Hg, a typical ventilation rate, and an average mixing factor. These variables can be changed to better reflect the actual situation and improve the predicted Hg concentrations. One of the variables that is difficult to predict is the evaporation rate of the Hg not initially released. The model assumes that the Hg is in liquid form but in actuality, the Hg is in other forms (e.g., combined with the phosphor on the glass coating) and the vapor pressure of Hg in these forms does not appear to be well defined based on available literature.

Appendix B – Maine Report Clean-up Measures and Flooring Types

Table B-1 below describes the cleanup measures and types of flooring used for the initial six scenarios.

Table B-1. Six Planned Scenarios (taken from the Maine Report (Stahler et al., 2008))

Scenario	Floor Type	Cleanup	Hg Measurements[a]
S1	Wood	No lamp cleanup/ no ventilation	Measure air concentrations continuously until highest concentration is reached
S2	Wood	Pre-study cleanup guidance with modification for 3/8" hardware cloth as per Appendix D	Measure continuously
S3	Short Pile Rug	Pre-study cleanup guidance with modification for 3/8" hardware cloth as per Appendix D	Measure continuously
S4	Long Pile "shag" Rug	Pre-study cleanup guidance with modification for 3/8" hardware cloth as per Appendix D	Measure continuously
S5	Short Pile Rug	Ventilate room. Clean up glass over 3/8" by hand, vacuum, and remove waste pieces and vacuum bag from room	Measure continuously/ take discrete measurements at vacuum locations
S6	Long Pile "shag" Rug	Ventilate room. Clean up glass over 3/8" by hand, vacuum and remove waste from room	Measure continuously/ take discrete measurements at vacuum locations

[a]All measurements were taken at one foot and five foot above site of lamp break.
Note: All six scenarios used the same "Brand A" soft white A19 14 watt lamp type.

Table B-2 below summarizes the steps followed for each trial in the initial six Maine scenarios.

Table B-2. Summarizes the steps followed for each trial in the initial six Maine scenarios (taken from the Maine Report (Stahler et al., 2008))

All trials for cleanup scenarios (S2-S6) included the following basic steps:
1. Set up room with flooring in position adjacent to Lumex intake hoses, intakes set at 1' height from flooring and 5' height from flooring.
2. Close window and door. Record room temperature on the Project Daily Temperature Record each day.
3. Place CFL on hardware cloth over flooring surface and cover with vinyl plastic coverlet.
4. Begin monitoring room mercury concentrations.
5. Thoroughly break CFL by striking plastic covered CFL with hammer & move cover plastic to one side of box.
6. Ventilate room by opening the 30" x 38" window to the outside of the building.
7. Clean up lamp using chosen scenario cleanup.
8. Bag and properly dispose of broken lamp and cleanup materials outside study room.
9. Record mercury concentrations until measurements stabilize under 20 ng/m^3.
10. Close outside window and let mercury concentrations equilibrate to check for rebound.
11. Measure and record mercury vapor concentrations outside room door during study to confirm that levels do not exceed ambient air guidelines.
12. Bag and properly dispose of any remaining mercury contaminated materials and decontaminate room by venting. Room mercury concentrations must stabilize under 50 ng/m^3 before proceeding to the next trial.
Scenario 1 included all of the above steps except that the room was not vented (step 6 in list) and the cleanup steps (steps 7, 8, 10 and 12 in list) were not completed.
The usual time between break and cleanup was one to five minutes.

Table B-3 below describes the cleanup measures and types of flooring used for the remaining scenarios tested.

Table B-3. Additional Scenarios (taken from the Maine Report (Stahler et al., 2008))

Scenario	CFL Type*	Floor Type	Cleanup
SA	"Brand B" 26w=90watts	Wood	Same as scenario 2
SB	"Brand C" 13w=60watts	Short pile rug	Same as scenario 2
SC	"Brand D" 14w=60watts	Wood	Same as scenario 2
SD	"Brand A" 14w=60watts	Wood	Same as scenario 2, except CFL turned on for approx. 1 hr before break to be "hot"
SE	"Brand B" 26w=100watt	Wood	Same as scenario 2
SF	"Brand B" 26w=100watt	Wood	Same as scenario 2, except vent for 46 minutes before cleanup.
SG	"Brand D" 23w=100watt	Wood	Same as scenario 2, except vent for 11 minutes before cleanup
SH	"Brand E", 15w=60watt	Wood	Same as scenario, except vent for 7 minutes before cleanup
SI	"Brand F" R30 15w=50watt	Wood	Same as scenario 2, except vent for 5 minutes before cleanup
SJ	"Brand A" 14w=60watt	Wood	Same as scenario 2 except CFL cracked instead of thoroughly broken.
SK	"Brand B" 26w=90watts	Long pile "shag" rug	Same as scenario 6
S5T3 Revacuum	Previously cleaned up "Brand A" 14w=60watt	Short pile rug from S5T3	No venting Re-vacuum once
SB Vac1	Previously cleaned up	Short pile rug	No venting

SB Vac2	"Brand C" 13w=60watts	from SB	Vacuum four times.
SB Vac3			
SB Vac4			
SB Vac1	"Brand B" 26w=100watt	Short pile rug	No venting, clean up big pieces and put in room trash, vacuum rest of debris and leave in room. Vacuum four times.
SB Vac2			
SB Vac3			
SB Vac4			

* "Brand A" soft white, 14w=60watts, ave. lumens=800, ave. life=8,000hrs.
* "Brand B" = Energy Choice, 26w=90watts, ave. lumens=1500, ave. life=10,000hrs.
* "Brand B" 26w=100watt, ave. lumens=1700, ave. life=8,000hrs
* "Brand C" = Soft White, 13w=60watts, ave. lumens=800, ave. life=8,000hrs.
* "Brand D" soft white, 14w=60watts, ave. lumens=900, ave. life=10,000hrs., model EDXO-14
* "Brand D" soft white, 23w=100watt, ave. lumens=1600, ave. life=10,000hrs.
* "Brand E", 15w=60watt, ave. lumens=1050, ave. life=10,000hrs, model H150275
* "Brand F" R30 soft white reflector (dimmable), 15w=50watt, ave. lumens=500, ave. life=6,000hrs, "amalgam technology"

Appendix C – Repeated Vacuuming Data

Data extracted from table Appendix A for all SL Scenarios from the Maine Report (Stahler et al., 1008).

Scenario	Lamp type	Maximum[a]	<300[b]	1 hour Ave[c]	8 hour Ave[d]	24 hour Ave[e]
SL One trial at two heights ▪ Break on short pile rug. ▪ No ventilation, clean up only big pieces and put in trash in room, vacuum rest of debris with a Hoover 850 beater vacuum. ▪ Measure continuously.	"Brand B" 26w, 100 watt equivalent	At 5 feet 23,720 At 1 foot 133,955	At 5 feet: >1,500 At 1 foot: >1,500	At 5 feet 16,814 At 1 foot 21,262	At 5 feet: 12,364 At 1 foot: 14,384	At 5 feet: 4,490 At 1 foot: 5,130
SLvac2 One trial at two heights ▪ No new bulbs were broken as a part of this scenario. This was a re-vacuum of SL short nap carpet. This carpet had been previously vacuumed as a means of cleaning up a lamp breakage 4 days earlier. It was vacuumed with a Hoover 850 beater vacuum. ▪ This is the second vacuum of the carpet. ▪ Otherwise same as SL.	"Brand B" 26w, 100 watt equivalent Broken and cleaned up 4 days earlier.	At 5 feet 3,135 At 1 foot 36,397	At 5 feet: 530.75 At 1 foot: >1,200 spikes[16]	At 5 feet 2,623 At 1 foot 2,444	At 5 feet: 1,429 At 1 foot: 1,471	At 5 feet: 691 (20 hour average) At 1 foot: 729 (20 hour average)
SLvac3 One trial at two heights ▪ This carpet had been previously vacuumed as a means of cleaning up a lamp breakage 5 days earlier. ▪ This is the third vacuum of the carpet w/ same vac. ▪ Otherwise same as SL.	"Brand B" 26w, 100 watt equivalent Broken and cleaned up 5 days earlier	At 5 feet 3,708 At 1 foot 19,270	At 5 feet: 539.33 At 1 foot: >1,200 spikes[17]	At 5 feet 2,671 At 1 foot 2,768	At 5 feet: 2,590 At 1 foot: 2,587	At 5 feet: 1,038 (20.5 hour average) At 1 foot: 1,236 (20 hour average)

[a] Still spiking over 1,000 ng/m3.

Scenario	Lamp type	Maximum[a]	<300[b]	1 hour Ave[c]	8 hour Ave[d]	24 hour Ave[e]
SLvac4 One trial at two heights ▪ This carpet had been previously vacuumed as a means of cleaning up a lamp breakage 6 days earlier. ▪ This is the 4th vacuum of the carpet with same vac. ▪ Otherwise same as SL.	"Brand B" 26w, 100 watt equivalent Broken and cleaned up 6 days earlier.	At 5 feet 3,288 At 1 foot 12,367	At 5 feet: 523.75 At 1 foot: >1,200 spikes[18]	At 5 feet 1,986 At 1 foot 1,871	At 5 feet: 1,502 At 1 foot: 2,244	At 5 feet: 574 (20 hour average) At 1 foot: 1,085 (20 hour average)
SLcarpet One trial at two heights ▪ Carpet alone in room after SLvac4. Room ventilated prior to placing carpet square in room. ▪ Measure Continuously.	"Brand B" 26w, 100 watt equivalent Broken and cleaned up 7 days earlier.	At 5 feet 1,186 At 1 foot 5,679	At 5 feet: 652.42 At 1 foot: >1,600 spikes over 800 ng/m3	At 5 feet 135 At 1 foot 699	At 5 feet: 491 At 1 foot: 1,056	At 5 feet: 255 At 1 foot: 561

a Maximum = the maximum mercury concentration observed during trial including lamp break and cleanup in ng/m3
b below 300= the time (minutes) elapsed between lamp break and when concentrations at he identified intake fell below 300 ng/m3
c 1 hour average = the mercury concentration (ng/m3) averaged over one hour from the lamp break
d 8 hour average = the mercury concentration (ng/m3) averaged over 8 hours from the lamp break
e 24-hour average = the mercury concentration (ng/m3) averaged over 24 hours from he lamp break