Remediation of Indoor Airborne Mercury Released from Broken Fluorescent Lamps

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I. Introduction

This paper addresses and models the dynamics of airborne mercury potentially released from a Compact Fluorescent Lamp (CFL) in the event of breakage in a home. CFLs are recommended as energy efficient replacements for incandescent bulbs for domestic and commercial lighting. A typical 60 W incandescent bulb can be replaced by an equivalent 15 W CFL resulting in significant energy savings. CFLs are designed as "drop-in" replacements for incandescent bulbs is most domestic lighting fixtures, with the exception of rheostatically controlled (dimmable) units

Considering the number of incandescent bulbs used in a typical home, the potential energy savings garnered from replacement of all incandescent bulbs in a home is significant. The CFL is four times as efficient as the incandescent bulb and also has the added benefit of emitting very little heat. By contrast, most of the energy dissipated by incandescent lamps is in the form of heat or infrared radiation. The use of CFLs would therefore reduce the heat load on air-conditioning systems, resulting in additional energy savings. Moreover, CFLs have much longer lifetimes, as much as ten times the lifetime of typical incandescent lamps. A CFL will pay for itself in energy savings in less than a year.

Despite the compelling economics in favor of CFLs, concerns have been raised about the presence of mercury in CFLs and the potential for the release of that mercury in the event of accidental breakage. A typical CFL contains about 4-5 milligrams (5 mg = 0.005 g) of mercury [1]. The mercury resides in the curved tubular glass shell that constitutes the light emitting surface of the CFL.

Prior to the introduction of CFLs, the most common fluorescent lamp was the four-foot linear T8 fluorescent lamp. These lamps are commonly used in commercial and office lighting, but are also found in some residential settings such as garages, basements and workshops. According to surveys conducted by the National Electrical Manufacturer's Association (NEMA), the average mercury content [3, 4] of a four-foot lamp declined from 48.2 mg in 1985 to 22.8 mg in 1994 to 11.6 mg in 1999 to 8.3 milligrams in 2001. In a study of four-foot fluorescent lamps by Maine's Department of Environmental Protection

[5], the average amount of mercury in T8 and T12 lamps manufactured in the year 2000 from three of the nation's largest manufacturers, GE, Sylvania and Phillips was found to vary between 3.2 mg and 6 mg per lamp by vendor and model. The typical T8 lamp sold today has between 3 and 8 mg of mercury.

The U.S. EPA and Florida DEP's Hazardous Waste Management section provide guidelines [1, 6] for the cleanup of solid debris and mercury containing residues resulting from the breakage of a fluorescent lamp. While most of the mercury present in the lamp is released into the air as vapor-phase elemental mercury, a small amount of residual mercury will remain adsorbed on the solid debris including broken glass and phosphor powder resulting from the breakage of the lamp. It is important to remove these solids as specified in the guidelines [1, 6] to ensure that no additional mercury is emitted to the room over an extended period. The model described here shows that with the proper cleanup of debris, it is possible to lower the concentration of airborne mercury in the room to ambient (outdoor) levels in as little as 20-25 minutes by following some simple measures such as opening windows and using a table or pedestal fan to vent the room.

II. Toxicity Characteristics

The mercury present in the CFL is in the form of elemental or atomic mercury. The toxicity of mercury is critically dependent upon its chemical state, with some forms being many orders of magnitude more toxic than others. Fortunately, elemental mercury is among the least toxic forms of mercury. We will assume that upon breakage all of the mercury is released to the air in elemental form. We will show that this is a reasonable assumption based on the calculation in the box below. The suggested chronic Minimal Risk Level (MRL) for indoor mercury [7] developed by the Agency for Toxic Substances and Disease Registry (ATSDR) is 0.2 micrograms per cubic meter ($\mu g/m^3$). This value is less than (more restrictive than) the U.S. EPA Reference Concentration (RfC) of 0.3 $\mu g/m^3$. We will show that is possible to achieve mercury concentrations below the MRL of 0.2 $\mu g/m^3$ in as little as 20 minutes by opening a window and venting the air in the room using a simple table fan or pedestal fan.

Estimation of the Volume of Mercury i n a CFL

The tubular glass shell of a CFL is filled with an inert gas such as argon along with a small amount (~5 mg) of mercury. One can estimate the approximate volume of the mercury enclosed in a CFL by noting that the density of elemental mercury is 13.6 g/ml. The volume of a droplet of 5 mg of mercury is 3.7×10^{-4} ml or 0.37 microliters (µl). This is a microscopic volume of mercury, and would barely cover the tip of a pin [2].

The mercury in the CFL is evenly dispersed within the glass confines of the CFL and is in the gas phase during operation, when the CFL is warm to the touch. At room temperature, some of this mercury will condense to a thin film adsorbed on the phosphors coating the inner walls of the glass envelope, with a significant fraction still in the gas phase due to the element's significant vapor pressure. Thus when a CFL breaks, the likelihood of a (visible) droplet of liquid mercury physically landing on the floor is very remote. Rather, the bulk of the mercury is released immediately in the gas phase with a small amount remaining adsorbed on the surface of the now broken glass surface of the CFL.

In the event of breakage of an older (10 year old) 4-foot T8 lamp, with say 25 mg of mercury in it, the volume of the mercury will be 1.85 µl or 1.85×10^{-3} ml. The mercury in the T8 lamp is dispersed over a much larger surface area of phosphor and glass. As in the case of CFLs, the bulk of the mercury in the T8 lamp will also be released as gas phase elemental mercury upon breakage. However, a larger fraction of the mercury is likely to remain adsorbed on the phosphor dust and glass, given the substantially larger area of the T8 glass tube relative to the CFL. As stated previously, a thorough clean up of this debris is important.

Since the bulk of the released mercury is airborne, the most practical way to clear the mercury in the room is to vent the room's air outdoors by means of forced airflow using a household fan such as a table fan or pedestal fan. We have assumed that fresh (outdoor) air is allowed to enter the room through a second open window or door to replace the air vented from the room.

III. Mathematical Model

For the sake of generality, it is necessary to make some reasonable assumptions which should be representative of typical scenarios found in domestic residences. We will assume the affected room to have dimensions of 12 ft ×12 ft with a ceiling at a height of 8 ft. The volume of the room will be 1152 ft^3 or 32.6 m^3. The room shall possess at least one or more windows through which indoor air can be vented outdoors by means of a fan. At a minimum, the room possesses one window and an entryway (door) through which fresh air can enter the room to replace the air that is vented by the fan. We will assume that the fan vents the air in the room at a constant rate of 20 cubic feet per minute or 0.57 cubic meters per minute. This is a conservative estimate and most domestic table or pedestal fans can move air at far greater rates.

Even in pristine environments, fresh (outdoor) air contains traces of mercury. Clean outdoor air has mercury levels ranging from 1.5 to 2 ng/m^3. We assume our outdoor air to have a constant value of 2 ng/m^3 or 0.002 $\mu g/m^3$. We have seen from a previous calculation, that most of the mercury in the CFL is released to the room as gas phase elemental mercury upon breakage. This will result in a spike in the concentration of airborne mercury in the room's air immediately after breakage.

We assume that the mercury vapor released from the broken CFL will disperse rapidly in the room and attain a near-uniform concentration in the room's air within a few minutes. The dimensions of the room are small enough for this assumption to be reasonably valid. In reality, there will likely be a small gradient, with higher concentrations of mercury present at lower levels, close to the floor and to the spot where the CFL breaks. Once the fan is turned on however, the resulting air flow will reduce these gradients and enhance mixing to create a more uniform concentration profile.

The model described above takes the general form of a compartment model as illustrated in Figure 1. Let C_0 denote the ambient background outdoor concentration of mercury in $\mu g/m^3$. Let V denote the volume of air in the room. Let A denote the rate at which air is vented from the room in cubic meters per minute. Fresh outdoor air enters the room at the same rate at which it is being vented.

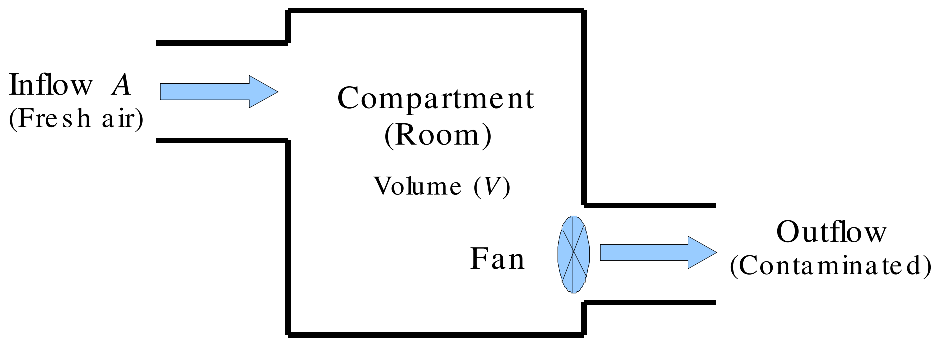

Figure 1: Conceptual model of the room and airflow

The rate at which ambient mercury enters the room will be AC_0 µg/min. The parameters of the model are:

C_0 = 0.002 µg/m^3 = 5.66 × 10^{-5} µg/ft^3

A = 0.57 m^3/min = 20 ft^3/min

and V = 32.6 m^3 = 1152 ft^3

For the purpose of this study, we are interested in events only *after* the breakage of the lamp. Thus, the value of time will be set to zero at the moment the CFL breaks. We assume there is no significant delay (~ 5 minutes) between the instant the CFL breaks and when a window is opened and a fan turned on to ventilate the room.

Let *y(t)* denote the amount of mercury in the room at time *t*. Then *y'* = *dy/dt* denotes the rate of change of mercury in the room.

y' = *dy/dt* = Hg inflow rate – Hg outflow rate

$= AC_0 - A\,y = A(C_0 - y)$ µg/min

The separation of variables yields

$$\frac{dy}{C_0 - y} = Adt \quad \text{or} \quad \frac{dy}{y - C_0} = -Adt$$

Integrating the above expression yields

$\ln|y - C_0| = -At + k'$ where *k'* is the constant of integration.

Taking exponentials on both sides one obtains,

$$y - C_0 = e^{-(At-k')} = Ke^{-At} \qquad \text{or}$$

$$y = C_0 + Ke^{-At} \quad \text{Equ. (1)}$$

<u>Initial value</u>: At the time the CFL breaks, we assume that all the mercury in the CFL becomes airborne. Thus, 5 mg or 5000 μg of mercury is evenly dispersed in the room's air. The final concentration of mercury in the room will be the sum of the preexisting background concentration (C_0) and the newly released mercury. The flow of air through the room is triggered when the fan in turned on (t = 0).

Thus, the concentration of mercury in the room = $y\ (t = 0) = C_0 + 5000 / V$ μg/m^3. Substituting this value in equation (1), one obtains

$$C_0 + \frac{5000}{V} = C_0 + Ke^0 = C_0 + K \quad \text{or} \quad K = \frac{5000}{V}$$

Thus the concentration of mercury in the room at time t is given by

$$y = C_0 + \frac{5000}{V} e^{-At} \quad \text{Equ. (2)}$$

The second term in equation (2) represents the exponential decay of the mercury concentration from the initial spike after breakage *(5000/V)*, decaying rapidly to values close to zero. The decay is represented by the exponential term e^{-At}. The rate of decay increases as the airflow rate A increases, since the mercury is being vented away from the room at a faster rate. Without additional releases, the concentration of airborne mercury will quickly approach C_0, the background concentration of mercury in outdoor air. For the parameters we have chosen, $C_0 = 0.002$ μg/m^3 , $V = 32.6$ m^3 and $A = 0.57$ m^3/min, the concentration of mercury in μg/m^3 is given by

$$y = C_0 + \frac{5000}{32.6} e^{-0.57t} = 0.002 + 153.4e^{-0.57t} \quad \text{Equ. (3)}$$

One can choose different units, using $C_0 = 5.66 \times 10^{-5}$ μg/ft^3 , $V = 1152$ ft^3 and $A = 20$ ft^3/min. The concentration of mercury in μg/ft^3 then becomes

$$y = C_0 + \frac{5000}{1152} e^{-20t} = 5.66 \times 10^{-5} + 4.34 e^{-20t} \quad \text{.........................} \quad \text{Equ. (4)}$$

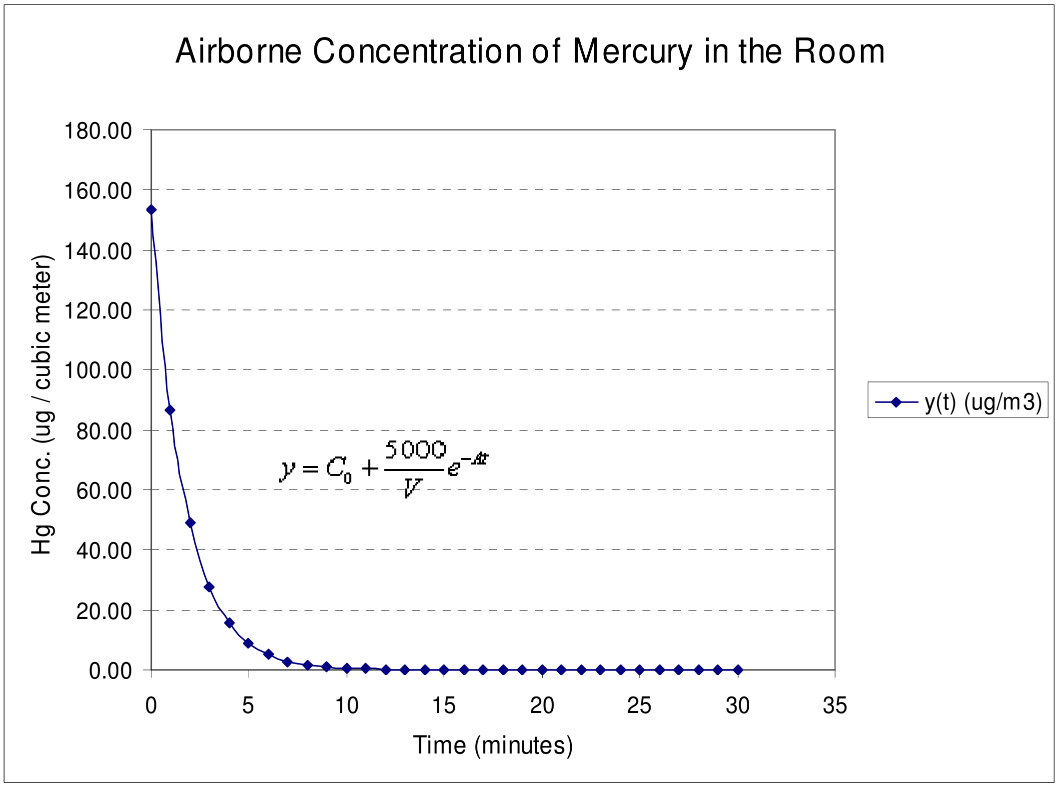

Figure 2: Dynamics of Airborne Mercury in a Room

Figure 2 shows a plot of the concentration of mercury given by equation (3) or equation (4). Airborne mercury levels in the room drop to below the Minimum Risk Level (MRL) of 0.2 µg/m^3 within twelve minutes of ventilation with the fan and down to ambient background (outdoor) levels within twenty two minutes of ventilating the room. For an older four-foot T8 lamp containing a nominal 25 mg of mercury, the corresponding ventilation times in the same room using the same fan would be fifteen minutes to lower airborne concentrations below the MRL and twenty five minutes to lower mercury levels to ambient levels.

An interactive spreadsheet model (**Mercury_CFL_Model.xls**) has been developed that automatically calculates and plots the graph shown in Figure 2 for selected values of the parameters C_0, A and V [8]. The nominal value of the amount of mercury in the CFL can also be changed in the spreadsheet model.

IV. Recommendations

A fact-sheet on CFLs and mercury issued by Energystar [1] recommends that in the event of breakage of a CFL, the resident should scoop up glass fragments and any powder deposited on the floor, followed by wiping the area with a damp paper towel or disposable wet wipe. Sticky tape such as duct tape or packaging tape can be used to pick up small pieces and powder. It then recommends opening a window and leaving the room for fifteen minutes to "air-out" the room.

We too believe that a thorough cleanup of glass fragments and phosphor powder is necessary. In addition, the resident can achieve rapid and more dependable results by taking a more pro-active approach in the last step, by using a fan to facilitate the movement and turn-over of air in the room. The use of a fan should allow mercury levels in the room to drop to background (outdoor) levels in less than 25 minutes even in the event of mercury releases from an older T80 lamp with 4-5 times the mercury in a typical CFL. One can choose to leave the fan on for half an hour to forty minutes for an additional margin of safety, but at the end of this period the room should have the same concentration of mercury as outdoor air and be ready for re-occupancy and normal use.

V. Conclusion

This paper shows that mercury released from a single broken CFL or a four-foot T80 lamp in domestic settings can be rapidly reduced to ambient outdoor levels, using simple measures that are effective and easy to implement by the layperson. Virtually all of the airborne mercury released from a broken lamp can be cleared by using a fan to vent the room's air outdoors, through an open window. Sweeping and removal of the residue from the broken lamp, including glass fragments and phosphor powder is critical to achieving a sustainable clean environment within the room that is safe for normal use.

VI. Acknowledgements

I would like to thank my colleagues at the Florida DEP, Dr. Don Axelrad of DEP's Environmental Assessment section from the Bureau of Laboratories, and Jack Price from the Division of Hazardous Waste Management for suggesting the topic and providing me the opportunity to work on this problem. We would also like to thank Dr. Christopher Teaf of Florida State University, Dr. Steve Lindberg, formerly of Oak Ridge National Laboratory, Dr. Frank Marsik of the University of Michigan and Laurie Tenace of Florida DEP for reviewing this paper and proving helpful suggestions and comments.

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