MERCURY EMISSIONS FROM THE DISPOSAL OF FLUORESCENT LAMPS

FINAL REPORT

Office of Solid Waste
U.S. Environmental Protection Agency

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BACKGROUND

Most fluorescent lamps contain quantities of mercury sufficient to fail the Toxicity Characteristic (TC) and are subject to the hazardous waste regulations under the Resource Conversation and Recovery Act (RCRA) when discarded.[1] (See 40 CFR 261.24.) However, many generators do not realize that their spent mercury-containing lamps are hazardous waste and thus do not manage them in compliance with the RCRA hazardous waste regulations. On July 27, 1994, the U.S. Environmental Protection Agency (EPA) published a proposed rule addressing the management of spent mercury-containing lamps (59 FR 39288). In the proposal, the Agency presented two options for changing the regulations governing spent mercury-containing lamps:

- Add mercury-containing lamps to the universal waste regulations (UW option).
  - ♦ Under this option, spent mercury-containing lamps that failed the TC would be subject to universal waste regulations. (See 40 CFR Part 273 for existing universal waste regulations applicable to specified types of spent batteries, pesticides, and thermostats.) The proposed standards for generators and consolidation points of spent lamps include procedures for maintaining the condition of lamps (e.g., proper packaging), and storing the lamps (e.g., storage time limits, labeling), notifying EPA as specified, and responding to releases. The proposed standards for transporters of spent lamps include procedures for proper packaging of broken/unbroken lamps, storing and treating lamps (e.g., dilution prohibition), and responding to releases. Destination sites (e.g., landfills and recyclers) receiving spent lamps would be subject to the RCRA hazardous waste regulations at 40 CFR Part 264-270 and 124, as applicable.
- Conditionally exempt mercury-containing lamps from regulation as hazardous waste (CE option).
  - ♦ Under this option, generators would qualify for the exemption if they satisfy two conditions:
    - Generators would be required to either dispose of these lamps in a municipal landfill that is permitted by a state/Tribe with an EPA-approved municipal solid waste permitting program, or
    - If generators do not send these lamps to a municipal solid waste landfill, they would send them to a state permitted, licensed, or registered mercury reclamation facility; and
    - Generators must keep records of the lamps shipped to management facilities.

[1] Some data suggest that despite results of the Toxicity Characteristic Leaching Procedure, very little mercury leaches to groundwater from lamp disposal in landfills.

- Generators would be able to ship their lamps as part of their municipal waste stream, avoiding the RCRA hazardous waste generator standards (e.g., manifesting, recordkeeping), and ship the lamps to either a Subtitle C or D landfill, or a reclamation facility.

Note that the proposed options would apply only to generators generating more than 100 kg/month of hazardous waste or more than one kg/month of acute hazardous waste. That is, neither option would apply to RCRA conditionally exempt small quantity generators (CESQGs), which are generators generating quantities of hazardous waste below these thresholds. Although they too generate spent mercury-containing lamps, CESQGs are free under RCRA to send their hazardous waste (including spent mercury-containing lamps) to an approved Subtitle C or D landfill, or a reclamation facility.

In the 1994 proposal, the Agency identified uncertainties regarding the amount of mercury released from spent fluorescent lamps in the waste management system. The Agency requested information on, among other things, the amount of mercury released from broken mercury-containing lamps and the air transport of mercury from lamps. The Agency has also requested comment on best management practices and controls that might best prevent releases of mercury to the environment under both options. Since the proposal, EPA has continued to compile and analyze information provided by industry and other interested parties on mercury emissions from spent fluorescent lamps.

In June 1997, the Agency finalized development of the Mercury Emissions Model, which is designed to assist interested parties in examining the amounts and sources of mercury emissions that might be produced in managing and disposing of spent lamps under the options. The model provides emissions estimates for a modeling period extending from 1998 to 2007. Emissions estimates include both disposal emissions and net emissions. Installation of energy-efficient T8 lamps will reduce demand for electricity, which in turn reduces mercury emissions from utility boilers (in particular, coal-fired boilers). Net mercury emissions are defined as the difference between disposal emissions and the emissions avoided from energy savings.

PURPOSE OF REPORT

The purpose of this report is to discuss the methodology, data and assumptions used in developing the Mercury Emissions Model, with the objective of allowing users to understand its function and results. The report describes inputs into the model for estimating mercury emissions during waste management and disposal activities (e.g., lamp properties, lamp disposal rates, and lamp mercury emissions rates from specific waste management practices). It also discusses inputs for estimating the energy savings from using high-efficiency T8 lamps, and the effects on mercury emissions from electric utilities. It then presents the model's estimates for lamp mercury emissions under the baseline and options, including annual and cumulative mercury lamp disposal emissions, and net mercury emissions. In addition, the report presents sensitivity runs conducted to evaluate the extent to which the model's data and assumptions on mercury emissions during transport of spent lamps affect the mercury disposal emissions estimates under the CE option. The report also discusses key model limitations.

MODEL APPROACH

The model uses three basic elements to estimate mercury emissions from the management and disposal of lamps: mercury input into the waste management system; mercury emissions from the management and disposal of lamps; and the mercury emissions avoided from coal-fired utility boilers as a result of replacing T12 lamps with higher efficiency T8 lamps.

MERCURY INPUT

The mercury input into the model is a function of the number of lamp types entering the system and the quantity of mercury in the lamps. The number of lamps entering the waste management system is a function of the overall lamp population, which in turn depends on the following factors:

- The operating life and hours of operation for the types of lamps;
- The amount of floorspace lit with fluorescent lamps; and
- The relative population and mix of lamp types. (Please note that the model is designed to estimate total mercury emissions from the management and disposal of spent fluorescent lamps. Therefore, the model includes lamp populations from all generators, including generators subject to RCRA as well as CESQGs. Users of the model, however, should not conclude that CESQG lamps would be regulated under the options.)

EMISSIONS FROM MANAGEMENT AND DISPOSAL OF LAMPS

Mercury emissions from spent lamps are a function of the types and emissions rates of the waste management and disposal activities undertaken by waste handlers. Because of the scarcity of data, the model examines possible emissions outcomes based on low, central, and high estimates of emissions factors. The model estimates mercury emissions produced from the following waste management and disposal activities:

- Transport under RCRA Subtitles C and D. (Please note that the model defines transportation to include all activities from the time the lamp is spent until it is received at the first facility away from the site of generation);
- Crushing (i.e., as used as a volume reduction technique);
- Landfilling under RCRA Subtitles C and D;
- Combustion at Municipal Waste Combustors (MWCs); and
- Recycling.

MERCURY EMISSIONS AVOIDED FROM UTILITY BOILERS

Installation of high-efficiency T8 lamps will reduce the demand for electricity, which will in turn reduce the amount of mercury emissions from utility boilers, particularly coal-fired boilers. The model calculates energy savings based on the estimated energy savings per T8 lamp, total T8 population, delamping rates, and energy consumption of T12 lamps. From this, the model calculates mercury emissions avoided based on emissions factors for elemental, divalent, and particle species of mercury. The model also estimates net mercury emissions by calculating the difference between mercury emissions from lamp disposal and mercury emissions from coal-fired boilers that are avoided by using T8 lamps.

CONCLUSIONS

Based on the model's results, a number of observations and conclusions can be drawn. First, the Mercury Report to Congress estimates mercury emissions at about 220,000 kg in 1992. The model estimates annual lamp disposal emissions to range from a high of about 2,191 kg (CE High) to a low of 95 kg (UW Low). Further, the results suggest that Subtitle C and D landfilling, in particular, would account for minimal lamp mercury emissions under either option. This is largely because, based on the data, the model assumes that most lamps are broken before being landfilled. Second, transportation emissions are an important contributor to total mercury emissions, particularly under the CE option. We believe that virtually all lamps would be broken during transport under the CE option unless conditions are added to address releases. (Transportation, as used here, covers all handling from the time the lamp becomes spent until its receipt at the destination facility.) Third, energy savings from the use of T8 lamps and the resultant decrease in mercury emissions from utility boilers appear to be independent of the policy options; that is, the Agency believes that the mix of T12 and T8 lamps purchased by commercial establishments would be independent of the policy established. Taken collectively, these observations suggest that, to reduce lamp mercury emissions under either option, procedures should be established that minimize emissions during transport and/or processing (e.g., crushing) of spent lamps.

1. INTRODUCTION

1.1 BACKGROUND

The disposal of mercury-containing fluorescent lamps and the status of these lamps under the Resource Conservation and Recovery Act (RCRA) is controversial. Most fluorescent lamps contain quantities of mercury sufficient to fail the Toxicity Characteristic (TC) and are, therefore, hazardous wastes under RCRA. However, many generators do not recognize that lamps can be hazardous waste, and do not manage lamps as hazardous waste. In addition, not all lamps are subject to hazardous waste regulations (i.e., household lamps and lamps generated by conditionally exempt small quantity generators).

On July 27, 1994, the U.S. Environmental Protection Agency (EPA) published a proposed rule addressing the management of spent mercury-containing lamps (59 FR 39288). In this proposal, EPA presented two options for changing the regulations governing mercury-containing lamps. One option was to add mercury-containing lamps to the universal waste regulations. Under the universal waste option, mercury-containing lamps that fail the TC would be subject to streamlined universal waste regulations. These would include, for example, less stringent transportation requirements that would make it easier for facilities to collect and send their wastes to hazardous waste management facilities.

The other option considered was to conditionally exempt mercury-containing lamps from regulation as hazardous waste. Under this option, mercury-containing lamps would not be considered hazardous provided they are disposed of in municipal solid waste landfills that meet certain criteria, or are recycled at mercury reclamation facilities that meet certain requirements. The Agency also asked for comment on a variety of additional conditions that might be beneficial under the conditional exclusion option.

Currently, the vast majority of the fluorescent lamp population consists of T12s, which contain on average 25 milligrams of mercury per lamp. T12s can be replaced with energy-saving T8s, which contain about 15 mg of mercury per lamp. Because utility boilers emit mercury, lamp manufacturers and utilities believe that the most effective means to reduce mercury emissions is to encourage the rapid transition from T12s to T8s through energy-savings programs.[2] It is contended that this transition would reduce mercury emissions by an amount greater than the emissions from the disposal process, and that the current status of lamps as a potential RCRA hazardous waste hinders this beneficial transition. Other parties believe mercury emissions from lamp disposal to be a significant and controllable source of mercury emissions. These parties believe that lamp disposal should be regulated as hazardous waste as a means to reduce emissions of mercury.

The Mercury Emissions Model was developed to address these and other issues regarding the management and disposal of fluorescent lamps. It is designed to answer questions regarding emissions from the disposal of fluorescent lamps under various policy options, and to be a flexible policy analysis tool allowing users to analyze the effects of various policy choices.

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[2] The Mercury Report to Congress indicates that utility boilers using natural gas or oil emit only small amounts of mercury and that the use of coal is responsible for most of the mercury emissions.

1.2 PURPOSE OF REPORT

In this report, the Agency presents the methodology and assumptions used to develop the model, with the objective of allowing users to understand its structure, function and limitations. The report presents the overall structure of the model, data and assumptions underlying emissions estimates, and emissions results for selected policy options. In the course of developing the model, the Agency uncovered facts relevant to lamp disposal issues, and these are presented as well. While the model is sufficiently flexible to allow users to develop and analyze policy options under a variety of conditions, the Agency focuses on the following three policy options:

1. Baseline Management - Baseline management assumes that no action is taken by the Agency and that current trends in the management of fluorescent lamps continue. Under the baseline, generators and other handlers of spent lamps would be subject to the RCRA hazardous waste regulations, as applicable, for lamps that fail the Toxicity Characteristic (TC). (See 40 CFR 261.24.) Under RCRA, conditionally exempt small quantity generators (CESQGs) (i.e., generators generating 100 kg/month of hazardous waste or less, or one kg/month or less of acute hazardous waste) can send their waste to a hazardous waste facility, or may elect to send their waste to a landfill or other facility approved by the State for industrial or municipal non-hazardous wastes. <u>CESQGs are not affected by either of the options</u>. Generators above the CESQG thresholds are required to fully comply with the RCRA hazardous waste regulations as applicable (e.g., waste characterization, manifesting, recordkeeping). In addition, transporters and destination facilities must follow the hazardous waste regulations in managing lamps from these generators.

2. Universal Waste (UW) -Under this option, mercury-containing lamps that fail the TC would be subject to streamlined universal waste regulations. The proposed universal waste standards for generators and consolidation points of spent lamps include procedures for maintaining the condition of lamps (e.g., proper packaging), and storing the lamps (e.g., storage time limits, labeling), notifying EPA as specified, and responding to releases. The proposed standards for transporters of spent lamps establish procedures for proper packaging of broken/unbroken lamps, storing and treating lamps (e.g., dilution prohibition), and responding to releases. Destination sites (e.g., landfills and recyclers) receiving spent lamps would be subject to the RCRA hazardous waste regulations at 40 CFR Part 264-270 and 124, as applicable. The proposal also establishes limited exporter requirements.

3. Conditional Exemption (CE) -Under this option, generators would qualify for the CE if they meet two conditions:

   - Generators would be required to either dispose of these lamps in a municipal landfill that is permitted by a state/Tribe with an EPA-approved municipal solid waste permitting program, or

   - If generators do not send these lamps to a municipal solid waste landfill, they would send them to a state permitted, licensed, or registered mercury reclamation facility; and

   - Generators must keep records of the lamps shipped to management facilities.

Under the CE option, generators would be able to ship their lamps as part of their municipal waste stream, avoiding the RCRA hazardous waste generator standards (e.g., manifesting, recordkeeping), and ship the lamps to a Subtitle D landfill or a reclamation facility. Under the CE, the Agency proposed to limit the exclusion to spent lamps disposed in municipal solid waste landfills, rather than allowing disposal in any nonhazardous waste landfill or a municipal solid waste combustor.

For each of these options, the model estimates net emissions by considering three factors. First, the model estimates the total quantity of mercury entering the disposal system. This is accomplished by estimating the total number of 4-foot lamps entering the waste management system in conjunction with estimates of the quantity of mercury in the lamps. Second, emissions from the disposal operations are estimated as a fraction of the quantity of mercury entering a specific disposal operation. Third, the model then estimates net emissions from the disposal process by subtracting the emissions avoided as a result of the installation of energy-saving lighting (i.e., mercury emissions avoided as a result of not generating electric power).

As with all models, there are limitations to the Mercury Emissions Model. Important limitations include the following:

- A major obstacle in developing the model was the scarcity of reliable data on certain aspects of lamp management and disposal, lamp mercury emissions, and mercury emissions from utility boilers. Much of the data and assumptions in the model are based on the Agency's best professional judgment (e.g., partitioning coefficients) and conversations with industry and states (e.g., emissions factors). The model partly compensates for this limitation by allowing users to estimate lamp mercury emissions based on a range of lamp mercury emissions factors. The model also allows users to manipulate selected other data and assumptions (e.g., partitioning coefficients). Finally, the model allows users to conduct sensitivity analyses to isolate the effects that a particular assumption may have on the model's emissions estimates.

- As currently structured, the model only considers commercial floorspace as defined in the report.

- The modeling period begins in 1992 and ends in 2007. Due to an assumed lamp life of four years, the model needs an initiation period, during which lamp populations are estimated. Therefore, the initial portions of the modeling period (1992-1996) are for this initiation. Policy options may begin in 1997 or any later year, and last for any specified duration that does not extend beyond 2007.

2. MODEL APPROACH

To estimate mercury emissions from the disposal of 4-foot fluorescent lamps, the model estimates three basic elements:

1. Mercury inputs into the waste management system. The mercury input is a function of the number of each lamp type (i.e., T12 and T8) entering the waste management system and the quantity of mercury in the lamps. The number of lamps entering the waste management system is a function of the overall lamp population, which in turn depends upon the following factors:

    - The operating life and hours of operation for the types of lamps;
    - The amount of floorspace lit with fluorescent lamps; and
    - The relative population mix of T12s and T8s (i.e., quantity of T12s replaced with T8s as part of energy-efficiency programs and the relative fraction of new floorspace lit with each type of lamp).

2. Emissions from the disposal of lamps. Mercury emissions are a function of the type of management units used during the transport and disposal process, and the emissions estimates from each type of unit. For purposes of this analysis, the Agency examines possible emissions outcomes based on low, central, and high estimates of emissions factors. Because of the scarcity of reliable data, we do not believe that our estimates of mercury emissions under the central estimate are any more accurate than those of the low or high estimates. "Central estimate" is simply the estimate that falls somewhere between the low and high estimates, but not necessarily at the midpoint.

3. The mercury emissions avoided from coal-fired utility boilers as a result of replacing T12s with higher efficiency T8s.

2.1 MERCURY INPUT

To estimate the quantity of mercury entering the disposal system, the Agency estimated the amount of commercial floorspace lit with fluorescent lamps, the floorspace growth rate, the mercury content of lamps, the relative population of lamps, and lamp lifetimes. We use these basic factors as discussed in the following sections to estimate the mercury quantities.

2.1.1 COMMERCIAL BUILDING SPACE GROWTH RATES

We used data from the Energy Information Administration (EIA) on total floorspace by building size category to estimate how many fluorescent lamps are used each year.[3] EIA estimates floorspace by type of lighting, but for the purposes of this report, the Agency used the "Total Fluorescent" value of 37,831,000,000 ft^2 as the 1986 starting point, as opposed to including unlit space, or space lit with either HID or incandescent lamps. We then updated this value to 1992 levels by assuming an annual growth rate of 1.024 percent. In total, the Agency estimates a total floorspace of 43,624,690,000 ft^2 for 1992.

[3] Energy Information Administration, Commercial Buildings Energy Consumption and Expenditures - 1992, DOE/EIA-0318(92), April 1995.

We categorized total floorspace into three building sizes shown in Table 2-1. The space allocation for 1992 is contained in the Commercial Building Allocation section of the model. Please note that the Agency analyzes only commercial floorspace because we believe that the vast majority of users of fluorescent lamps are commercial establishments. We define a commercial establishment as a building with more than 50 percent of its floorspace used for commercial activities. Commercial establishments include, but are not limited to, stores, offices, schools, churches, gymnasiums, libraries, museums, hospitals, clinics, warehouses, and jails. Government buildings are also included, except for buildings on site with restricted access (e.g., some military installations). "Lighted commercial floorspace" is the total amount of floorspace within commercial buildings that was lighted electrically.

Table 2-1. Building Categories

Building Group	Size Range (ft^2)	Median Size (ft^2)	Percentage of "Total Fluorescent"
Small	0 - 100,000	36,000	66
Medium	100,000 - 500,000	220,000	25
Large	> 500,000	770,500	9

Because the overall demand for lighting changes with economic activity and with the construction of new buildings, we estimated a rate of increase in the demand for lighting, which translates into a greater total number of lamps used each year. The estimated increase in lighting demand of 2.4 percent annually is based on the average increase in commercial building floorspace recorded annually between 1989 and 1992.[4]

2.1.2 LAMP PROPERTIES

We used available data to determine lamp lifetimes, delamping rates, the fraction of lamps entering the waste management system, and mercury content of lamps.

2.1.2.1 Lamp Lifetimes

Fluorescent lamp life varies from three to six years based on annual hours of use. Assuming that lamps are operated between 4,000 and 5,000 hours each year, and have a typical life of 20,000 hours, their life span is between four and six years. However, because some lamps fail before their typical end of life, the Agency assumed that lamps will have to be replaced every four years. Thus, we used a spot relamping rate of 25 percent (i.e., one-fourth of all lamps are replaced each year). We further assumed that, during spot relamping, lamps are replaced with other lamps of the same type (T8 or T12).

2.1.2.2 Delamping Rates

New participants to the Green Lights Program, EPA's voluntary program that encourages lighting efficiency, will initially do group relamping (i.e., change all of their lamps at once) to upgrade to the more efficient lamps (from T12 to T8). Furthermore, based on professional judgment, EPA assumed that 60 percent of the participants in Green Lights will continue to do group relamping after they join the program because it is more economical than spot relamping.

Building owners and operators conducting lighting upgrade programs tend to "delamp," i.e., reduce the number of lamps lighting the space. Many older buildings contain unnecessarily high numbers of bulbs

[4] Energy Information Administration, Commercial Buildings Characteristics - 1992, DOE/EIA-0246(92).

and/or fixtures per square ft. During upgrades, the bulbs and fixtures are redistributed to ensure more efficient lighting. This results in a decrease in the number of bulbs and/or fixtures in the building, thereby reducing the lamp population. Delamping rates vary, with some owners and operators choosing not to delamp and others making large changes. Therefore, in estimating the population of T8s, the Agency does not assume a one-to-one correspondence with T12s they replace. A one-to-one replacement rate is assumed for replacements of T12s with T12s, and T8s with T8s, but not for a transition from T12s to T8s. Based on experience with the Green Lights Program, we assumed a delamping rate of 0.85 (i.e., 85 T8s replace 100 T12s).

2.1.2.3 Lamps Entering Waste Management System

We used a binomial distribution to estimate the fraction of 4-foot lamps entering the waste management system. Based on professional judgment, we assumed an average life of four years and a maximum life of six years for both T12s and T8s. Thus, the portion of lamps entering the waste management system as a result of failure are:

$$\text{Fraction of Failed Lamps} = \frac{N!}{(N-K)!} P^{K} (1-P)^{(N-K)}$$

Where:

N = cohort year, which ranges from 1 to 6,
K = maximum lamplife, and
P = average lamplife

Thus, in any given year, the lamps entering the waste management system are the sum of:

- The number of failures in years 1, 2, 3, 4, 5, and 6 (note: by year 6 all of the lamps in a cohort have failed); and
- T12s replaced during group relamping operations.

2.1.2.4 Mercury Content of Lamps

The mercury content portion of the model contains information regarding the mercury content of each lamp type at the end of lamplife. Because the dummy lamp 'none' is unnecessary for this portion of the model, only five types of lamps are used. Information in the Mercury Report to Congress indicates that mercury deposition rates vary dramatically among species. [5] Therefore, it was decided to track mercury content in lamps by species, i.e., elemental mercury, divalent mercury, and particulate mercury. Data on overall mercury content were provided to EPA at meetings with manufacturers during the summer of 1996.[6,7,8] See Table 2-2 and 2-3. Manufacturers provided estimates of current and future mercury content, which were aggregated into an estimate of total mercury content for T12s and T8s.

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[5] United States Environmental Protection Agency, Mercury Study, Report To Congress: SAB Review Draft. EPA-452/R-96-001. June 1996.

[6] Paul Waltisky, Phillips Lighting Company to Ms. Kristina Meson, Environmental Protection Agency. Letter of September 30, 1996.

[7] Joseph Howley, GE Lighting to Ms. Kristina Meson and Ms. Yvette Hopkins, Environmental Protection Agency. Letter of August 20, 1996.

[8] Sylvania Corporation: Meeting notes and follow-up letter. Meeting between Ms. Kristina Meson, EPA technical staff, and personnel from Sylvania Corporation, August 21, 1996. Sylvania follow-up comments presented in letter dated September 18, 1996.

Apportionment into species is very uncertain and the Agency based its estimate on information from Sylvania, in conjunction with information provided by the National Electrical Manufacturers Association (NEMA).[9] Sylvania presented a limited data set indicating that the vapor phase mercury was primarily elemental, while mercury incorporated into the phosphor was primarily divalent. Information supplied by NEMA indicates the vapor phase content of the mercury is estimated to be 0.2 percent. Therefore, EPA assumed the elemental portion of the mercury at 0.2 percent, with the remainder being divalent. (Please note we assumed no particulate mercury, but allow for this possibility in the model structure.)

The total mercury content of lamps depends upon the type of lamp as well as the year of manufacture. Information from lamp manufacturers indicates that substantial reductions in the mercury content of lamps have already occurred, and more reductions are anticipated. Our assumptions regarding the mercury content of lamps as a function of year of manufacture and lamp type are as follows:

Table 2-2. Mercury Content Of T12 Lamps (milligrams per lamp)

Year	Elemental	Divalent	Particulate	Total
pre-1992	0.082	40.9180	0	41
1992-1996	0.06	29.94	0	30
1997 -2007	0.042	20.958	0	21

Table 2-3. Mercury Content Of T8 Lamps (milligrams per lamp)

Year	Elemental	Divalent	Particulate	Total
pre-1996	0.06	29.94	0	30
1996-1999	0.03	14.97	0	15
2000-2007	0.02	9.98	0	10

It should be noted that the 10 mg Hg value for T8 lamps between 2000 and 2007 represents the upper bound. Manufacturers report "less than 10 mg Hg."

2.1.3 RESULTS

The quantity of mercury is determined by calculating the number of lamps entering the waste management system, and the quantity of mercury in the lamps. To estimate lamp populations, the Agency estimated lamp densities for the three building size categories based on common building practices. Typically, one fluorescent fixture will cover 50 to 80 ft^2 of floorspace. In smaller private offices, one fixture is usually required for every 50 ft^2; for large open areas, one fixture is required for approximately 80 ft^2. We assumed that the smaller the building size, the lesser the amount of open office area.

To provide a recommended 50 foot-candles of lighting in the office space, the Agency assumed a fluorescent fixture will typically have three (3) 4-foot lamps. Assigning a fixture density for each building size (i.e., 50 ft^2 fixture for small, 65 ft^2 fixture for medium, and 80 ft^2 fixture for large), and

[9] Overall, the Agency believes the results of the emissions analysis are better viewed in terms of total mercury, than by species.

assuming that each fixture has three lamps, we calculated the following lamps per ft^2 for the three building sizes:

- Small - 0.06 lamps/ ft^2
- Medium - 0.046 lamps/ ft^2
- Large - 0.038 lamps/ ft^2

The total number of lamps is then estimated based on total square footage in each building size category and average lamp per ft^2. This methodology provides "the effective T12" population, which represents the numbers of lamps if the population consisted solely of T12s. To estimate the actual population, EPA accounted for delamping by decreasing the effective T12 population with 0.85 T8s per T12. Thus, the 1992 lamp population is developed as follows:

- Estimate the effective T12 population using the floorspace, lighting density, and building groups described above; and
- Estimate the T8 population using data from the Department of Commerce for shipments of T8s shown below.[10] Iterative runs of the model were performed until the 1992, 1993, and 1994 populations approximated the populations from these data. Domestic shipments of linear T8s between 1992 and 1994:
    - ♦ 1992: 27.1 million
    - ♦ 1993: 41.2 million
    - ♦ 1994: 53.3 million

Tables 2-4 and 2-5 present the resulting lamp populations and the numbers of lamps entering the waste management system.

2.1.4 RELATIONSHIP OF T8 POPULATIONS TO POLICY OPTIONS

In all scenarios we assume that T8 populations are independent of the policy option. This assumption is based on the following:

- Disposal costs are a small fraction of the upgrade to energy efficient lighting, generally accounting for less than 1 percent of the cost; and
- In a series of interviews with firms declining to participate in the Green Lights Program, lamp disposal costs and issues were never mentioned as a reason for not participating.

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[10] U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, Current Industry Reports – Electric Lamps, Summary 1992, (MQ36B (92)-5), September 1993, and Current Industry Reports – Electric Lamps, Summary 1993 (MQ36B (94)-1), November 1994.

Table 2-4. Lamp Populations (percent)

Scenario Name	Building Group	Lamp Types	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Base Case												
	Large											
		T12	49.0%	43.0%	37.8%	33.4%	29.7%	26.4%	23.7%	21.3%	19.3%	17.5%
		T8	51.0%	57.0%	62.2%	66.6%	70.4%	73.6%	76.4%	78.7%	80.8%	82.5%
			100.0%	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**
	Medium											
		T12	82.2%	78.9%	75.7%	72.7%	69.9%	67.2%	64.6%	62.2%	60.0%	57.8%
		T8	17.8%	21.2%	24.3%	27.3%	30.2%	32.9%	35.4%	37.8%	40.1%	42.2%
			100.0%	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**
	Small											
		T12	87.6%	84.9%	82.2%	79.7%	77.2%	74.9%	72.7%	70.6%	68.6%	66.6%
		T8	12.4%	15.2%	17.8%	20.4%	22.8%	25.1%	27.3%	29.4%	31.5%	33.4%
			100.0%	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Note: Lamp shares are calculated on lamp numbers after delamping.

Table 2-5. Annual Number of Lamps Disposed (millions)

Scenario/Building/Lamp		1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Base Case																	
Large	T12	47.59	44.52	41.72	42.77	42.78	38.56	34.75	31.18	27.93	25.09	22.65	20.56	18.73	17.12	15.72	14.53
Large	T8	1.32	3.56	6.20	9.95	14.77	19.85	24.67	29.55	34.36	38.71	42.59	46.19	49.61	52.84	55.89	58.78
Medium	T12	133.95	131.86	129.98	131.34	133.45	135.89	134.78	132.52	129.79	127.25	125.04	123.14	121.22	119.26	117.46	115.85
Medium	T8	1.09	3.24	5.87	9.55	14.35	20.61	27.30	34.54	42.46	50.63	58.60	66.34	74.11	81.95	89.78	97.59
Small	T12	443.97	441.17	438.96	451.72	462.81	471.76	472.58	469.08	463.76	458.99	455.22	452.35	449.24	445.81	442.84	440.38
Small	T8	1.55	5.22	9.80	17.21	28.06	43.94	61.99	82.18	104.46	127.52	150.15	172.39	194.87	217.73	240.72	263.80
		629.48	**629.58**	**632.52**	**662.53**	**696.22**	**730.60**	**756.08**	**779.05**	**802.77**	**828.18**	**854.24**	**880.97**	**907.77**	**934.70**	**962.412**	**990.92**

2.2 UTILITY BOILER MERCURY EMISSIONS SAVINGS

Installation of high efficiency lighting will reduce mercury emissions from coal-fired power plants. In this section the Agency provides an estimate of the mercury emissions avoided as a result. (Please note that neither oil-fired nor natural gas-fired plants emit significant amounts of mercury.) Therefore, EPA's focus is on coal-fired units.

Electrical Generation in the United States totaled 2,825,023,000,000 kilowatt hours (kwh) in 1991.[11] The Mercury Report To Congress estimates mercury emissions from coal-fired utility boilers as 46.3 megagrams per year (Mg/yr) from 1990 through 1993. We developed an emissions factor in milligrams per kwh by dividing the 46.3 Mg/yr of emissions by the electric generation of 2,825,023,000,000 kwh, which resulted in an emissions rate of 0.016 mg/kwh.

To estimate energy savings we estimate the energy consumption of typical T12 and T8 installations, and compare the energy usage. Most T12 lamps are used with "energy efficient (EE) magnetic ballasts" and there is a mix of 40-watt and 34-watt T12 lamps. The American National Standards Institute (ANSI) rated consumption for two 40-watt T12 lamps on a single EE magnetic ballast is approximately 88 watts.[12] The consumption of two 34-watt T12 lamps on the same ballast is 72 watts. We used the average of 80 watts per ballast to estimate an average energy use of 40 watts per T12 lamp.

The calculation of watts per lamp for T8 lamps is based on the assumption that two T8 lamps operate on one electronic ballast. ANSI reports total wattage consumption per ballast of 62 watts. Thus, **we** estimate 31 watts per T8 lamp.

Based on Green Lights data, EPA assumed that, on average, the total hours of lighting per year are 4,000 for T8 lamps and 4,500 for T12 lamps.[13] Thus, the Agency calculated energy use of 124 kwh/lamp/year for T8 lamps and 180 Kwh/lamp/year for T12 lamps. Hence a per lamp energy savings of 56 kwh per lamp. Please note that because of delamping, actual energy savings are higher than the 56 kwh/lamp.

To estimate the energy savings per T8 lamps, EPA includes both the per lamp energy savings provided by a T8 and the delamping rate. The calculation procedure is as follows:

Energy Savings for a T8 population = T8_pop(f*es + (1-f)* eT12); where:

T8_pop	=	the population of T8s;
f	=	the delamping rate, which is estimated as 0.85;
e_s	=	the per lamp energy savings, which is estimated as 56 kwh per lamp per year; and
e_{T12}	=	the energy use of a base T12, which is estimated as 180 kwh per year.

[11] Energy Information Administration. Electric Power Annual 1995, Volume I. July 1996

[12] United States Environmental Protection Agency, Office of Air and Radiation, Lighting Upgrade Technologies, EPA 430-B-95-008, February 1997.

[13] Typically, controls such as occupancy sensors are installed along with the more efficient lighting. These controls provide reduced hours of operation for T8s as compared to T12s.

We then used data from the Mercury Report To Congress, Volume III, Table 5-2 to separate the utility boiler emissions into elemental, divalent, and particulate emissions. Data from Table 5-2 indicate that approximately 50 percent of utility boiler mercury emissions are elemental, approximately 30 percent of mercury emissions are divalent, and the remaining 20 percent are particulate. We then applied these percentages to the mercury emissions rate of 0.016 mg/kwh, which results in the following speciated emissions rates:

- Elemental - 0.00819 mg/Kwh saved;
- Divalent - 0.00491 mg/Kwh saved; and
- Particle -0.00328 mg/Kwh saved.

Table 2-6 presents the net mercury emissions savings from the resulting T8 population for the CE High case. Please note that a major limitation of EPA's estimate of mercury emissions savings is that we assume a direct relationship between energy saved from using T8 lamps and a reduction in coal-fired electricity for all types of utility boilers; that is, the Agency assumes that, as the demand for energy decreases, there would be a corresponding decrease in coal-fired electricity for all utilities and regions of the country. Yet, lamp manufacturers and utilities have indicated that, for many parts of the country, the marginal demand for electricity during business hours would be satisfied by gas and oil units, not necessarily coal-fired units. For such regions, a decrease in energy demand would not necessarily result in a decrease in coal-fired electricity. This issue has not been resolved in the analysis.

Table 2-6. Electric Utility Mercury Emissions Avoided (kg)

Scenario Name	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Base Case										
Unadjusted	534.3	653.7	772.1	889.8	1006.9	1123.6	1240.1	1356.5	1473.1	1589.9
Base Savings	-534.3	-653.7	-772.1	-889.8	-1006.9	-1123.6	-1240.1	-1356.5	-1473.1	-1589.9
Net Savings	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
CE High T8 Growth										
Unadjusted	692.6	878.4	1056.7	1228.7	1395.6	1558.2	1717.2	1873.2	2026.7	2178.1
Base Savings	-534.3	-653.7	-772.1	-889.8	-1006.9	-1123.6	-1240.1	-1356.5	-1473.1	-1589.9
Net Savings	**158.4**	**224.7**	**284.5**	**338.9**	**388.7**	**434.6**	**477.1**	**516.7**	**553.6**	**588.2**

2.3 LAMP DISPOSAL EMISSIONS

In this section the Agency presents emissions rates for waste management units, and the flow of discarded lamps through waste management systems representing the policy options. Figures 2-1, 2-2, and 2-3 present ‘waste management trees’ for the policy options. Management trees consist of management units or steps (e.g., landfill, recycling, crushing, transport, etc.) and partitioning coefficients. Partitioning coefficients are the percentages of the lamp population flowing from one unit to the next (e.g., in Figure 2-1, we have partitioned the flow of lamps so that 20 percent flow into Subtitle C management). Functionally, the model performs as follows:

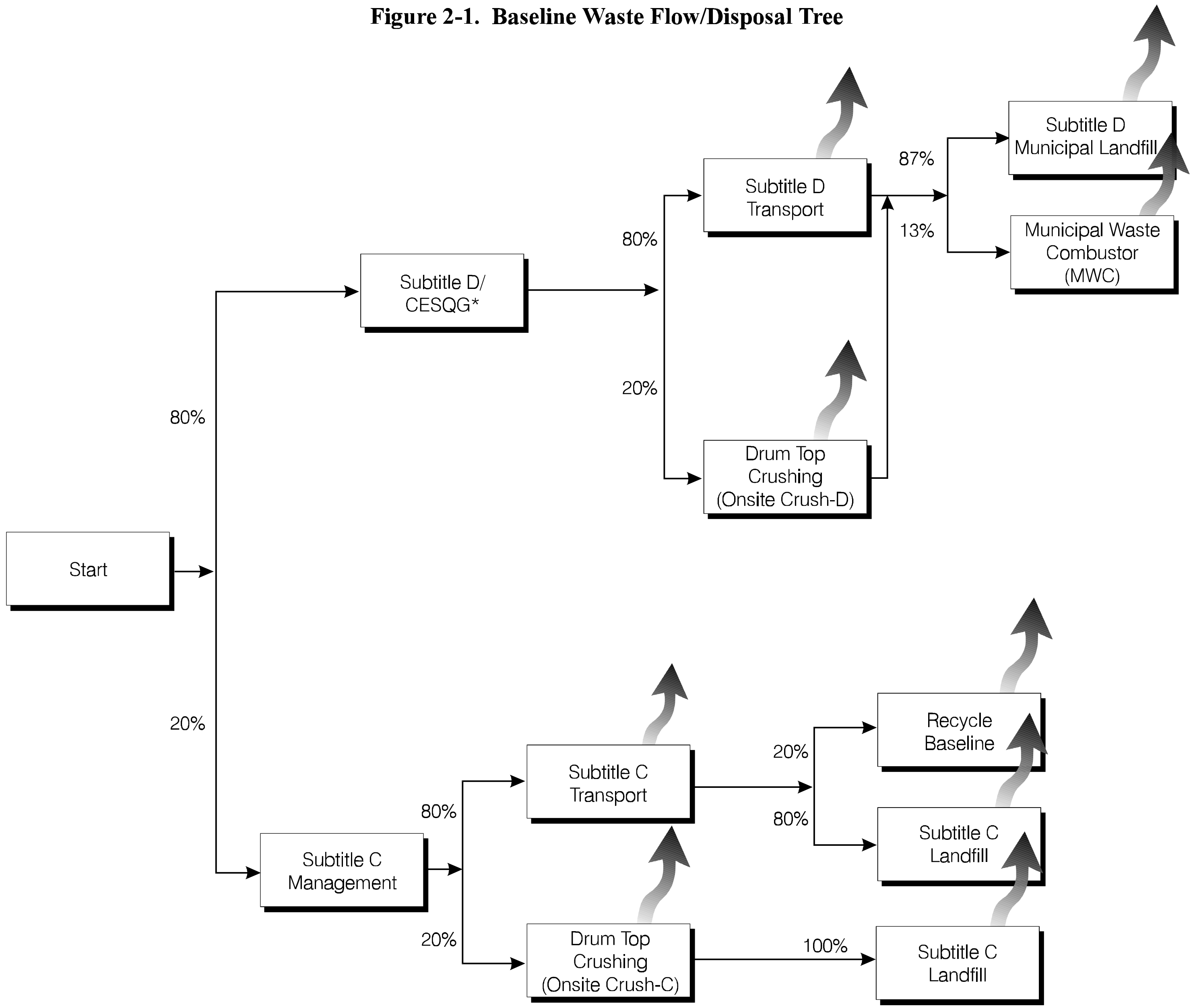
- The amount of mercury entering a disposal tree is estimated as discussed in Section 2.2.
- We track mercury by building group (i.e., large, medium, and small buildings) and lamp type (i.e., T12 and T8).
- We use “Partitioning Coefficients” to direct the flow of discarded lamps, and hence mercury, through the disposal tree. Partitioning coefficients are determined by:
    - ♦ Building group;
    - ♦ Lamp type; and
    - ♦ Year.
- We use emissions factors for each management step to estimate the emissions from each step. Emissions factors are by species. Again, emissions from each step are tracked by building group, by lamp type, and by year.
- We subtract the emissions from the quantity of mercury entering the step and the remaining mercury is transferred to the next steps as specified by the partitioning coefficients.

In the sections below, we describe first the emissions factors, followed by the partitioning coefficients.

2.3.1 EMISSIONS FACTORS

We applied available data and professional estimates to develop a range of mercury emissions for the unit operations comprising the lamp disposal system. For each management unit the Agency developed a low emissions estimate, a high emissions estimate, and a central estimate. Emissions rates are developed by species of mercury, and by year (i.e., the model has the capability to vary the emissions rates of disposal units by species by year, although this was not used as part of the analysis). The emissions rates are expressed as a percentage of the mercury emitted during the activity or unit, as a function of mercury species.

Figure 2-1. Baseline Waste Flow/Disposal Tree



**Conditionally Exempt Small Quantity Generators (CESQGs)*

Figure 2-2. CE Waste Flow/Disposal Tree

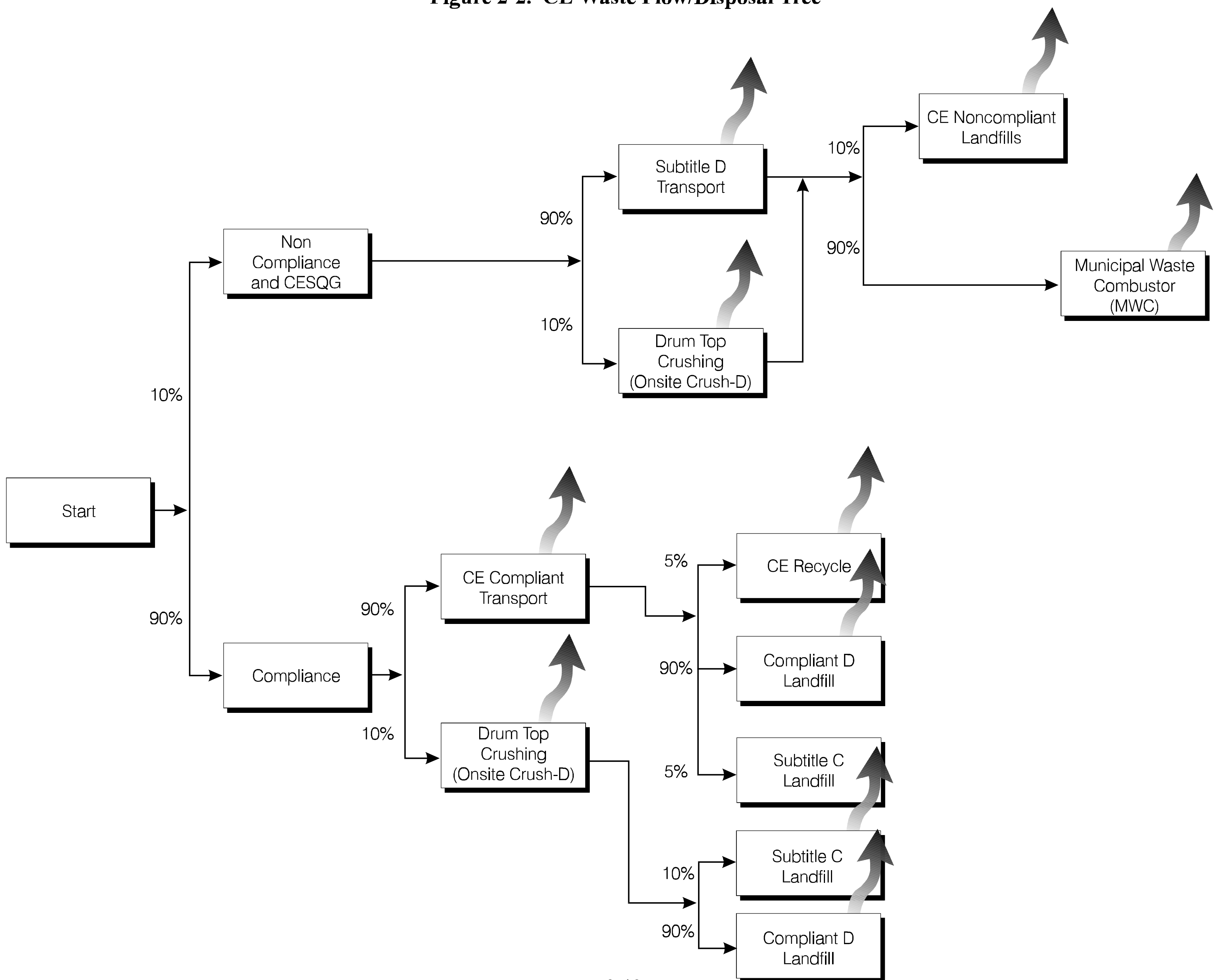
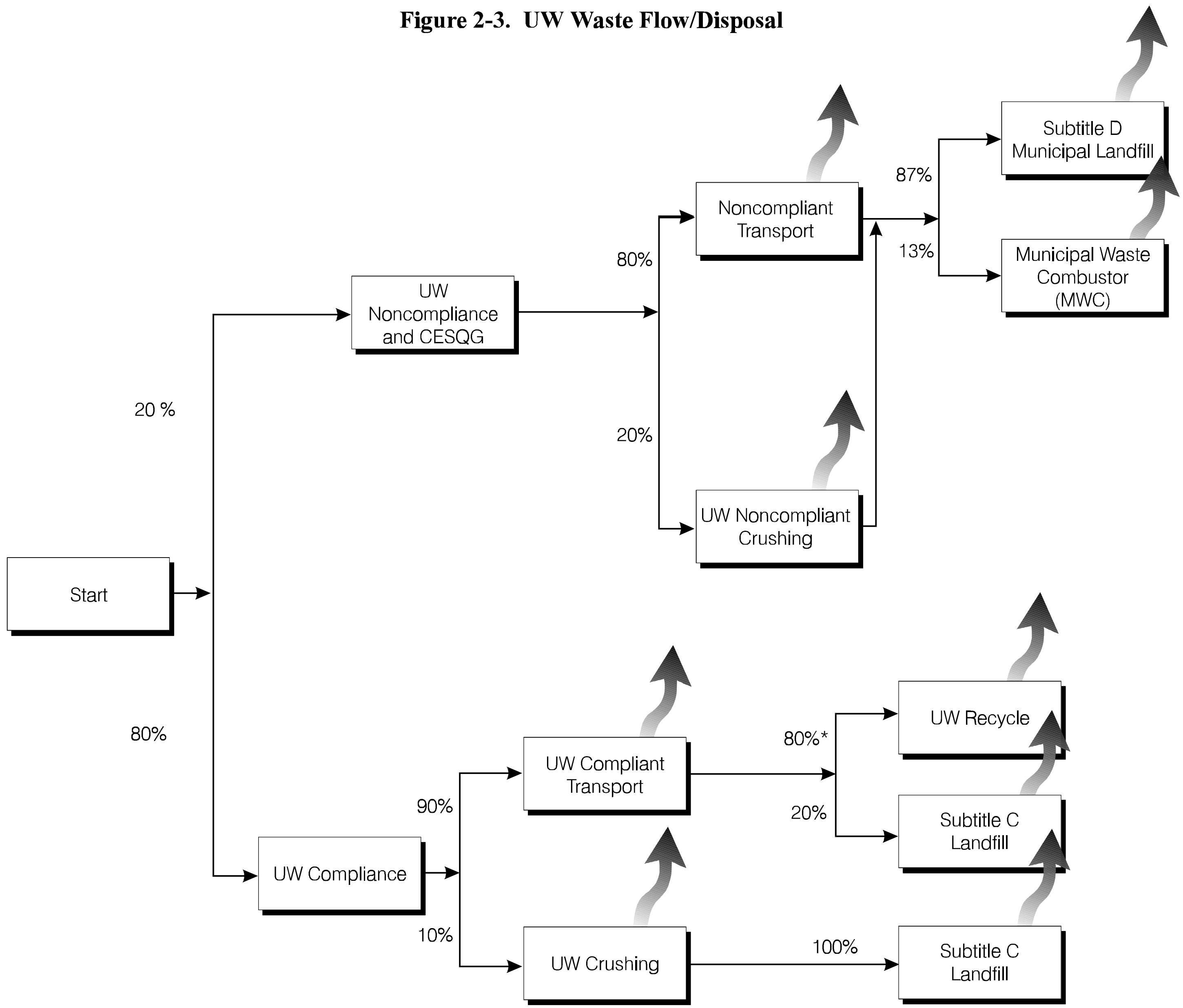


Figure 2-3. UW Waste Flow/Disposal



* After accounting for the percentage of lamps being managed under UW Compliant Transport, this 80% recycling rate translates into an "effective" recycling rate of 57%.

2.3.1.1 Transportation Emissions Rates

Transportation emissions arise from the breakage of the lamp between the point of generation and the final disposal operation. Emissions are a function of the mercury content of the lamp, the ability of the mercury to be emitted after breakage of the lamp, and the breakage rate (i.e., the fraction of lamps broken during the transportation operation). The first two factors represent an overall per lamp emissions rate, which when multiplied by the breakage rate, yields a mass emissions rate.

Some of the mercury in lamps is in the vapor phase, in which case it is assumed to be emitted immediately upon lamp breakage. Mercury is also incorporated into the components of the lamp (i.e., the phosphor powder, end caps, and glass). After breakage, the mercury must migrate from the phosphor, end caps, and glass prior to being emitted. For the purposes of estimating transportation emissions, the Agency assumes that the mercury incorporated into the glass and end caps is sufficiently bound that it will not be released without heat. Therefore, for the purposes of estimating unit emissions from lamps broken during the disposal process, the issues are:

- The quantity of mercury in the vapor phase;
- The quantity of mercury in the phosphor powder; and
- The quantity of mercury in the phosphor powder released after breakage.

Three sources of information addressing these issues were found. These are:

- Information contained in the "RTI report;”
- Information submitted by the manufacturers; and
- Information contained in the “Tetra Tech Report.”

Research Triangle Institute (RTI), under contract to EPA, developed emissions estimates from lamp breakage.[14] Overall, RTI estimates emissions from lamps after breakage to be about 6.8 percent of the total mercury content per lamp. In part, this estimate was derived from an estimate of the mercury content of the phosphor powder of about 5,000 ppm. RTI also used EPA emissions models such as CHEMDAT 7 to estimate migration of the mercury from the powder into the air. It should be noted that the 5,000 ppm estimate is based on 12 samples ranging from 868 ppm to 10,200 ppm. No explicit estimate of the vapor phase mercury is presented in the report.

NEMA presents emissions estimates that are somewhat lower. NEMA estimates that vapor phase mercury in non-operating lamps ranges from 0.06 to 0.2 percent of total mercury. Additionally, NEMA presents estimates that mercury emissions from broken lamps are at about 1 percent of total mercury. Thus, NEMA estimates emissions from lamp breakage in the range of 1 percent to 1.2 percent.[15] A report prepared for the Electric Power Research Institute (EPRI) by Tetra Tech Inc., measured mercury emissions from broken lamps with no cover, and soil and gravel covers of various

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[14] Truesdale, Robert S., et al., Research Triangle Institute, Management of Used Fluorescent Lamps: Preliminary Risk Assessment, October 1992 (Revised May 14,1993).

[15] National Electrical Manufacturers Association, Environmental Risk Analysis: Spent Mercury-Containing Lamps, A Summary of Current Studies, (second edition) February 20, 1995.

depths. For the uncovered broken lamp, emissions over a 20-day period totaled 1.28 mg out of the estimated total lamp content of 42 mg, or about three percent of the total mercury content of the lamp.[16]

Thus, estimates of overall emissions rates from broken lamps range from a low of about 1.2 percent of total mercury to a high of about 6.8 percent of total mercury (i.e., the range spans a factor of six). We used the RTI value as the high estimate, the NEMA value as the low estimate, and assumed a central estimate of three percent of total mercury. We assumed that 100 percent of the elemental mercury is in the vapor phase, and that this mercury accounts for 0.2 percent of the total mercury in the lamp at the end of lamplife.

In addition, crucial to the emissions from the transportation of discarded bulbs is the issue of breakage during transportation. Sources of information on this point include the RTI report and state environmental agencies. RTI assumes a breakage rate of 100 percent for lamps discarded in standard municipal waste. We believe this assumption to be reasonable for the following reasons:

- As part of a mercury control program, the State of Florida counted intact lamps on the pit of a municipal waste combustor in the Tampa area over a six-month period.[17] Only a comparatively small percentage of intact lamps were observed. This tends to confirm the RTI assumption of 100 percent breakage.

- It is not unreasonable to believe that lamps arriving intact at a Municipal Solid Waste landfill or transfer station will be broken during the handling operations or the landfill crush phase.

Therefore, a 100 percent breakage rate is assumed for lamps discarded as part of the non-hazardous solid waste stream.

Thus, for all activities associated with transport resembling Subtitle D management, the final emissions rate is simply the per bulb emissions rate multiplied by the assumed breakage rate of 100 percent. These emissions rates are shown below:

Table 2-7. Emissions Factors for Subtitle D and Similar Transport Per Lamp

Central Estimate		High Estimate		Low Estimate	
Elemental	Divalent	Elemental	Divalent	Elemental	Divalent
100%	2.8%	100%	6.8%	100%	1.1%

It should be noted that the 100 percent emissions rate for elemental mercury, again, results from the following:

- Vapor phase mercury is elemental;

- About 0.2 percent of the mercury content of the lamp will be vapor phase; and

[16] TetraTech Inc. and Frontier Geosciences Inc., Information on Fate of Mercury-Containing Lamps Disposed in Landfills. November 1994.

[17] State of Florida, Florida Department of Environmental Protection, 1995 Florida Mercury-Containing Lamp Recycling and 1996 Florida Mercury-Containing Lamp Recycling, May 20, 1997.

- All (100 percent) of the vapor phase mercury will be emitted during breakage.

We applied these emissions factors to the following units:

- Baseline Waste Flow/Disposal - Subtitle D Transport (see Figure 2-1);
- CE Waste Flow/Disposal - Subtitle D Transport and CE Compliant Transport (see Figure 2-2); and
- UW Waste Flow/Disposal - Noncompliant Transport (see Figure 2-3).

Available data indicate that breakage rates are lower than 100 percent during transport to recycling facilities. Information submitted by recycling facilities to the State of Florida indicate that breakage rates on shipments to recycling facilities averaged 0.2 percent during 1995. A recycling facility in the State of Maryland noted that breakage rates were significantly lower than one percent for properly packaged lamps, and as high as 25 percent for improperly packaged lamps. Facility personnel indicated that in an improperly packed box there was a strong tendency for the entire box to be broken. Overall, facility personnel seemed to believe that breakage rates on the order of one percent were typical of their operation. We also noted that some states (e.g., Minnesota) have regulations regarding breakage of shipments to recycling facilities. The regulations limit breakage to five percent beyond which point the shipment must be rejected.

The Agency developed emissions factors for transport to recycling facilities, and to Subtitle C landfills, by using the central tendency emissions factors in Table 2-7 (i.e., 100 percent for elemental and 2.8 percent for divalent) and varying the breakage rate. We used breakage rates of one percent for the central case, five percent for the high case, and 0.2 percent for the low case. The emissions factors are shown in Table 2-8.

Table 2-8. Emissions Factors for Transport to Recycling and Subtitle C Facilities

Central Estimate		High Estimate		Low Estimate	
Elemental	**Divalent**	**Elemental**	**Divalent**	**Elemental**	**Divalent**
1%	0.03%	5%	0.14%	0.2%	0.01%

We applied these emissions factors to "Subtitle C transport," which is used to represent transport to recycling and Subtitle C landfills.

2.3.1.2 Drum Top Crushing

Drum top crushing is a treatment technology providing volume reduction by crushing the lamps prior to transport. There are a wide variety of drum top crushers, ranging from simple devices with no emissions controls, to more complex systems with emissions controls. The more complex systems run under negative pressure, and are vented through a small carbon adsorber to reduce mercury emissions. Typically, such devices have counters that indicate when the carbon must be changed. Estimates of control efficiency provided by these devices vary from zero percent (for the uncontrolled case) to about 90 percent for the more complex devices. The 90 percent control level is based on a study by EPA's

Control Technology Center (CTC).[18] It should be noted that the meaning of the CTC estimate is unclear, and appears to indicate a control efficiency of 90 percent for the vapor phase mercury, which is only a small fraction of the mercury content of the lamp. It should be noted that drum top crushers are under negative pressure only during operation. When the device is not being actively used, the lamp feeding tubes and other openings may act as emissions points for mercury migrating out of the glass, phosphor, and end caps. Operational difficulties have also been reported. Specifically, leaks at the seal between the drum and the crusher have been responsible for violations of the OSHA mercury standard, and at least one instance of an inoperative counter also exists. Overall, there is little basis for assigning a control efficiency to drum top crushers equipped with controls, and there are no data indicating the populations of various types of crushers.

We developed a high emissions estimate by assuming no control, in which case the emissions rate should be about three percent of total mercury (i.e., identical to the 100 percent breakage case for Subtitle D transport). It should be noted, however, that emissions from an improperly operating crusher could be higher than emissions from the 100 percent breakage rate discussed above. This is because the crushing operation may eject the mercury containing phosphor powder into the air, thus forming a mercury-laden particulate.

We developed the central estimates as follows:

- Assume the Tetra Tech emissions estimate of three percent of total mercury is correct, the vapor phase mercury content of the lamp is 0.2 percent, and the emissions from the phosphor powder are 2.8 percent.
- Assume the carbon controls 90 percent of the estimated 0.2 percent of the mercury content that is estimated to be in the vapor phase (i.e., the post-control emissions are 0.02 percent).
- Assume no effective control on the remainder of the mercury (i.e., the emissions rate is 2.8 percent).
- Therefore, the central mercury emissions rate from crushing would be about 2.82 percent.

We developed the low emissions rate by assuming the carbon provides 90 percent control on both the vapor phase emissions and the mercury released by the phosphor. Table 2-9 presents the emissions rates for crushing operations.

Table 2-9. Emissions Factors for Crushing Operations

Central Estimate		High Estimate		Low Estimate	
Elemental	**Divalent**	**Elemental**	**Divalent**	**Elemental**	**Divalent**
10%	2.8%	100%	2.8%	10%	0.28%

2.3.1.3 Recycling Emissions

Some mercury-containing lamps are recycled. The mercury in the vapor phase and phosphor powder can be recovered, as can the glass and aluminum end caps. In the recycling process, the lamps

[18] United States Environmental Protection Agency, Office of Air Quality Planning and Standards, Control Technology Center, Evaluation of Mercury Emissions from Fluorescent Lamp Crushing. EPA-453/D-94-018. February 1994.

are crushed and separated into glass, end caps, and phosphor powder. The phosphor contains the majority of the mercury, and mercury is recovered from the powder in a retorting or other process. The recovered glass is used in the manufacture of fiber glass or road products, and the aluminum end caps are recycled in typical secondary aluminum operations (e.g., smelting). For the purposes of this study, mercury recycling is meant to cover the crushing and separation operations as well as the retorting and recovery of mercury. We refer to the recycling of glass and end caps as secondary recycling operations. Emissions factors used in this analysis account for emissions at primary recycling facilities, as well as emissions from secondary recycling processes.

Various estimates of mercury recycling emissions have been made. RTI estimates that emissions from a well managed facility could range from 0.2 to 0.4 percent of total mercury, and a well managed facility using advanced equipment will have overall mercury recovery rates of 99 percent of total mercury.[19] Thus, as estimated by RTI the fate apportionment of mercury in the recycling process is as follows:

- Recovered 99 percent
- Primary Emissions 0.3 percent
- Secondary Emissions 0.7 percent

RTI assumes that the 0.7 percent contained in the glass and end caps will be emitted during the recycling of those residuals. Thus, RTI concludes that emissions from the overall recycling process are about one percent of total mercury entering the facility. These RTI estimates are based upon data from a European manufacturer of recycling equipment.

The State of Florida, as part of their regulatory efforts, has obtained data from recycling operations within the state. Florida's estimated apportionment is as follows:

- Recovered 97 percent
- Primary Emissions << 1 percent
- Secondary Emissions 3 percent

This apportionment is based upon measurements of mercury concentrations in the residuals, in conjunction with estimates of the mass of the residuals. Representatives of the State of Florida indicated that results appeared to be driven by the high concentration of mercury in the end caps, and that the mercury in the end caps appeared to be concentrated in the filament. Also, NEMA cites sources indicating that overall releases from recycling including recovered material to be about three percent of total mercury.

In developing the range of emissions estimates, the Agency used the Florida and NEMA estimates for the central estimate and RTI for the low estimate. Because recycling operations are typically equipped with emissions control devices (typically a carbon adsorber), we assumed a 90 percent control efficiency on the vapor phase/elemental mercury for the central estimate, an 85 percent control efficiency for the high estimate, and no emissions for the low estimate. Based on Florida and NEMA, the

[19] Truesdale, Robert S., et al., Research Triangle Institute, Management of Used Fluorescent Lamps: Preliminary Risk Assessment , October 1992 (Revised May 14,1993).

Agency used an emissions factor of three percent of the divalent mercury for the central estimate. For the low case we used the RTI estimate of 99 percent recovered, and therefore, assumed an emissions rate of one percent, which the Agency ascribes to the divalent portion of the mercury. Table 2-10 presents emissions estimates for recycling units in all waste flow/disposal trees.

Table 2-10. Emissions Factors for Recycling Units

Central Estimate		High Estimate		Low Estimate	
Elemental	**Divalent**	**Elemental**	**Divalent**	**Elemental**	**Divalent**
10%	3%	15%	6%	0%	1%

2.3.1.4 Municipal Waste Combustor (MWC) Emissions

Management of mercury-containing lamps in MWCs will result in mercury emissions to the atmosphere. Evaluation of the available data led RTI to conclude that 90 percent of the mercury fed into a MWC not equipped with mercury controls (e.g., activated carbon BEPS) would be emitted as part of the flue gas, with the remaining mercury in the fly ash (5 percent) and the bottom ash (5 percent). These conclusions appear to be reasonable, and the 90 percent emissions rate was incorporated into the model for uncontrolled MWCs.

EPA's Office of Air Quality Planning and Standards (OAQPS) promulgated a series of emissions standards for new facilities and guidelines for existing MWCs.[20] These regulations will require all MWC units located at MWC plants with capacities of 35 megagrams per day (~38.5 tons per day) to reduce mercury emissions to 0.080 mg/dscm or by 85 percent by 1998.

The central emissions estimate was developed by assuming all of the vapor phase mercury, and therefore, all of elemental mercury has been emitted prior to reaching the MWC, and hence there is no elemental mercury left to emit. On this basis the Agency assigned a zero percent emissions rate for elemental mercury, and applied the 85 percent control efficiency to the divalent mercury.

Average control efficiencies can be either higher or lower than those specified in a regulation. Generally, to achieve a specified minimum control level (e.g., 85 percent reduction), owners and operators must achieve an average control efficiency higher then the control efficiency specified in the regulation. In this way owners and operators protect themselves against minor operating problems and excursions from routine operations. Based on information from OAQPS, EPA developed the low emissions estimate by assuming that an average control efficiency of 92 percent would be achieved. Again, the Agency assumed zero emissions of elemental mercury and applied this control efficiency to the divalent portion of the mercury.

Control efficiencies can also be lower than those specified in regulations. In evaluating State Implementation Plans (SIPs), OAQPS generally assumes, and requires states to assume, that rules will be less than 100 percent effective. This assumption accounts for deliberate noncompliance, enforcement difficulties, control device failures, and other difficulties. This is typically expressed as 'rule effectiveness,' and OAQPS typically uses a rule effectiveness value of 80 percent.[21] We applied a rule

[20] United States Environmental Protection Agency, Standards of Performance for Municipal Waste Combustors – Direct Final Rule, Federal Register, Vol. 60, No. 243, Tuesday, December 19, 1995.

[21] For example, given a regulation that should reduce emissions by 1000 tons per year at 100 percent compliance, applying a rule effectiveness value of 80 percent will result in a reduction of 800 tons per year.

effectiveness value of 80 percent to both the high emissions case (resulting control efficiency of 73 percent) and the low efficiency case (resulting control efficiency of 68 percent) and used a 70 percent control efficiency to represent the low case. This equates to an emission rate of 30 percent, which **we** use as the high estimate.

Table 2-11 presents the emissions factors for MWCs. We applied these factors for all MWC units.

Table 2-11. Emissions Factors for MWC

Central Estimate		**High Estimate**		**Low Estimate**	
Elemental	**Divalent**	**Elemental**	**Divalent**	**Elemental**	**Divalent**
0%	15%	0%	30%	0%	8%

2.3.1.5 Landfill Emissions

It is necessary to estimate lamp emissions rates for both Subtitle D Municipal Solid Waste Landfills (Subtitle D) and Subtitle C Hazardous Waste Landfills (Subtitle C). Information on Subtitle D emissions rates include RTI, NEMA, and the recent Fresh Kills Landfill Final Report.

RTI reviewed the available data on mercury releases from landfills, and concluded that the release rates for mercury in landfill gas leachates are very low. RTI calculated mercury landfill emissions of 0.8 kg/yr, nationwide. RTI used total mercury input of 643 Mg/yr to estimate that 0.0001 percent of mercury input to the landfill is emitted. RTI provided a final estimate of less than 0.00001 percent by assuming that mercury emissions from the bulbs is 3.8 percent (i.e., the percentage of mercury in municipal solid waste attributed to lamps). The data reviewed were taken mainly from Subtitle D facilities prior to 1990. Some commentors to the lamps rule have cautioned that the pre-1990 methods for measuring ambient mercury were imprecise and inaccurate. Thus, there is some doubt as to the validity of the low value reported by RTI.

Within the Tetra Tech study, mercury emissions from broken bulbs were measured under soil cover depths of 0.5 ft. and 1.0 ft. Results from the study indicate that releases from 0.5 ft. soil cover system averaged 0.8 percent of the total mercury content over a 20-day period, while the system with 1 ft. of cover averaged releases of 0.2 percent of total mercury content over a 20-day period. This study, performed in 1995, indicates emissions approximately three orders of magnitude higher than the RTI estimate.

Final estimates based on data from the Fresh Kills landfill in New York State are also available. Results of the report indicate that total mercury emissions from this landfill, which is among the largest in the United States, were about 2.4 pounds per year[22]. The report provides no estimate of the mercury entering the landfill. We provide a rough estimate of the amount of mercury entering the landfill as follows. We estimate the total population of lamps entering the waste management system in 1996 as 597 million. The population of the United States is approximately 260 million. On average there are slightly more than two bulbs disposed per person. Assuming the population served by Fresh Kills is about seven million, approximately 14 million bulbs should be disposed in the landfill each year. Based on the mercury content of T12s, each bulb contains about 30 mg of mercury.

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[22] McGaughey, James F., et al. Eastern Research Group. Mercury and Other Metals Testing at the GSF Energy Inc. Landfill Gas Recovery Plant at the Fresh Kills Landfill; Final Report. January 1997. See Tables 2-18 and 2-19.

Using these assumptions the mercury input to the landfill would be about 420 kg, resulting in an emissions rate of about 0.2 percent. Because there are other sources of mercury entering the landfill, this estimate should be considered as a crude approximation of an upper bound.

We developed the range of emissions estimates by assuming that remaining vapor phase mercury would be emitted during breakage at the landfill. We rounded the Tetra Tech estimate to one percent and used it as the upper bound estimate. We used the Fresh Kills 0.2 percent as the central estimate, and the RTI value of 0.00001 percent as the low estimate. The factors are presented in Table 2-12 and used for Subtitle D Landfill, CE Noncompliant Landfill, Compliant D Landfill and Subtitle D Landfill.

Table 2-12. Emissions Factors for Subtitle D Landfills

Central Estimate		High Estimate		Low Estimate	
Elemental	**Divalent**	**Elemental**	**Divalent**	**Elemental**	**Divalent**
100%	0.2%	100%	1.0%	100%	0.00001%

No studies specific to mercury emissions from Subtitle C landfills were found. We note that the Land Disposal Restrictions (LDRs) for hazardous wastes require stabilization prior to final disposal. Typical stabilization process for mercury involve incorporating the waste into a matrix such as cement or concrete. No estimates of emissions from the stabilization process or from the stabilized material are available. To estimate emissions from Subtitle C landfills, the following assumptions are made:

- Intact lamps received are crushed in the stabilization process; thus, any vapor phase mercury will be emptied during this process;

- Drums of crushed lamps undergo stabilization immediately after the container is opened; and

- Emissions from the stabilized material are zero.

Thus, the emissions factors for Subtitle C landfills are 100 percent for elemental mercury and zero for divalent mercury.

2.3.2 WASTE FLOWS AND PARTITIONING COEFFICIENTS

A critical issue in the development of the model is estimating the percentage of lamps undergoing the various management methods. Little data addressing the fate of lamps are available. Therefore, the approach taken is to use supplemental available data with assumptions to estimate waste flows within the policy options. Partitioning coefficients are estimates we developed for the flow schematics to represent the percentage of spent lamps being sent by generators of spent lamps into specific waste management processes under each of the options.

2.3.2.1 Baseline Management Waste Flows

There is general agreement that most existing lamps, when tested properly, fail the TC for mercury and are, therefore, hazardous waste under RCRA regulations. There is also a general consensus that comparatively few lamps are managed as hazardous waste. Many lamps are eligible to be disposed under 40 CFR 261.5 requirements, which allow generators of less than 100 kg/month of hazardous waste to dispose of this waste in Subtitle D landfills. As shown below, the Agency believes that most office buildings and commercial establishments generating lamps would fall within the CESQG provisions.

Based on the lamp weights reported by RTI, monthly generation of about 350 4-foot lamps per month would be necessary to exceed the 100 kg/month threshold for CESQGs, which equates to about 4,200 lamps discarded per year. Assuming spot relamping and an average lifetime of four years per lamp, we estimate a lamp population in the building of about 16,800 lamps. We may now use the lamp density to determine the size of the building necessary to generate 100 kg/month of spent lamps. Using the large building lamp density of 0.038 lamps/ ft^2, the Agency estimates that 442,000 ft^2 are necessary to generate 350 lamps per month. Based on the building size distribution presented by EIA, we would expect on the order of 10 percent of the total commercial floorspace to be in a building of this size or larger. Using the medium building lamp density in the calculation of 0.046 lamps/ ft^2 results in a building size of about 365,000 ft^2. Comparing this to the EIA size distribution, we conclude that less than 22 percent of the buildings are sufficiently large to generate 100 kg/month of lamps per month.[23] In considering these results, it should be remembered that some facilities will generate other hazardous wastes, and thus may fall above the 100 kg/month threshold at much smaller building sizes. However, given the small fraction of group relamping, in medium and small buildings in particular, it does not seem unreasonable to assume that approximately 80 to 90 percent of lamps are disposed in the Subtitle D portion of the Baseline management disposal tree. It must be remembered that this analysis only applies to spot relamping. Building owners and operators conducting a group relamping will generate over 350 lamps during the month in which the relamping occurs.

To examine this assumption further, the Agency noted that some states make efforts to keep lamps out of the Subtitle D management system. These states include California, Florida, Minnesota, and Wisconsin.[24] Because we were unable to obtain estimates of commercial floorspace for these states, the Agency used employment and establishments in the following Standard Industrial Classification (SIC) codes as a surrogate for floorspace:

- Wholesale Trade — SIC 50-51
- Retail Trade — SIC 52-59
- Finance, Insurance, Real Estate — SIC 60-67
- Services — SIC 70-87

We found that these states represent about 21 percent of employment in these SIC codes, and about 20 percent of establishments. Assuming that lighting scales with employment or establishments, it is not unreasonable to assume that about 20 percent of the lamps are discarded in these states, which require management outside of Subtitle D.

Based on these considerations we selected partitioning coefficients of 80 percent to Subtitle D and 20 percent to Subtitle C for the Baseline management scenario to represent the national totals. See Figure 2-1 which illustrates the Baseline waste flow/disposal tree.

Next, for the 80 percent in Subtitle D, the Agency partitioned among Subtitle D transportation, and drum-top crushing. There are no data on which to base the partitioning coefficients in this portion of the model. We noted that crushing as a volume reduction techniques is cost-effective for group relamping, and large buildings. The model indicates that about five to 10 percent of the total lamps discarded each year are the result of group relamping, and about 25 percent of those are from large buildings. Large buildings (about 10 percent of the floorspace) may find crushing an economical

[23] It must be remembered that this analysis only applies to spot relamping. Building owners and operators conducting a group relamping will generate over 350 lamps during the month in which the relamping occurs.

[24] Communications with states: California (March 9, 1993); Florida (November 23, 1994 and July 1996); Minnesota (August 23, 1996); and Wisconsin (February 26, 1993).

volume reduction technique. Therefore, we assumed partitioning coefficient into drum-top crushing of 20 percent, and correspondingly set the partitioning coefficient into Subtitle D transportation at 80 percent.

Subtitle D Transportation and drum top crushing are followed by the same management units; i.e., they are both followed by Subtitle D Landfill and MWC. The portion of lamps entering MWC units is assumed to be equivalent to the portion of solid waste managed in these units (i.e., about 13 percent) nationally, and the remainder are managed in Subtitle D Landfills (i.e., 87 percent).

In developing partitioning coefficients for the Subtitle C management portion of the tree, the Agency used the same 80 percent 20 percent split between Subtitle C transportation and drum-top crushing. We assumed that all lamps entering Subtitle C landfills are crushed and stabilized. The basis of this simplifying assumption is that crushing reduces transportation costs and that landfill operators prefer to receive crushed lamps while recycling unit operators prefer to receive intact lamps. Thus the partitioning coefficient from drum-top crushing to Subtitle C landfill is 100 percent.

Subtitle C transport can be followed by two management units: recycling or Subtitle C landfilling. We assumed that about 20 percent of lamps are recycled with the remaining 80 percent being managed in Subtitle C landfills. These partitioning coefficients are based on: discussions with owners/operators of Subtitle C Landfills who stated preferences for receiving crushed lamps; discussions with recyclers who asserted that they prefer intact lamps; and the fact that crushed lamps are less expensive to transport than intact lamps. Therefore, as shown in Figure 2-1, we make the simplifying assumption that 100 percent of the bulbs that are crushed go to Subtitle C landfills.

2.3.2.2 Conditional Exemption (CE) Waste Flows

In developing partitioning coefficients for CE we made the following assumptions:

- We assume a 90 percent compliance rate starting in 1998, which remains unchanged throughout the modeling period. We base this premise on the fact that CE compliance is a relativity simple matter.

- Overall, the Agency assumes that crushing declines under the CE option. We base this assumption on the fact that it is very convenient to simply dispose of lamps as part of the routine trash. Therefore, we assumed crushing rates of 10 percent for both the compliant and noncompliant/CESQG portion of the disposal tree. Please note that, while the central emissions estimates are approximately the same, the high and low emissions estimates differ with crushing having lower emissions (see Table 2-9).

- Within the noncompliant portion of the disposal tree, we assumed a partitioning between noncompliant landfills and MWCs of 10 percent and 90 percent. While the Agency believes the predominate noncompliant management would be transfer to MWCs, not all Subtitle D landfills comply with requirements in CE. Therefore, we assumed a small (10 percent) fraction of noncompliant landfills.

- Within the compliance portion of the disposal tree, we assume the majority of lamps undergo disposal in CE compliant transport (i.e., throwing the bulbs away in the trash) (90 percent). Of the lamps that undergo CE compliant transport, the predominant compliance technique is Subtitle D landfill disposal (90 percent), and the remaining 10 percent are equally apportioned among recycling and Subtitle C landfills.

- For crushed lamps, the Agency assumed that the predominate disposal technique is Subtitle D landfill disposal (90 percent), with the remainder being transferred to Subtitle C landfills. See Figure 2-2, which illustrates the CE waste flow.

2.3.2.3 Universal Waste (UW) Waste Flows

We assume UW should increase recycling compared with Baseline and CE, but there is uncertainty both in the timing and extent of this increase. Therefore, we examined three variants on the UW. In the absence of any predictions about waste flows within the system, we conducted a sensitivity analysis to determine how emissions would change, based on three variants of partitioning coefficients. The first, UW-rapid, represents an almost instantaneous increase in compliance and recycling. The partitioning coefficients shown in Figure 2-3 begin in 1998 and remain constant throughout the modeling period. Thus, the Agency models a rapid change from a mainly Subtitle D Baseline to a highly compliant UW scenario. The second variant, UW moderate, begins with relatively low partitioning between UW Compliance (20 percent) and UW Noncompliance and CESQG (80 percent) and smoothly rises to 80 percent compliance in 2005. Within this variant, the partitioning between UW recycling and Subtitle C landfilling is held at 80 percent and 20 percent, respectively, for the duration of the modeling period. Thus, while overall compliance increases steadily, the predominate compliance technique is recycling. The third variant, UW gradual, uses the same slow increase in compliance as the UW moderate, but adds a similar slow increase in recycling rates over the Baseline; that is, the partitioning between recycling and Subtitle C landfilling begins at 20 percent and 80 percent in 1998, respectively, and shifts smoothly over to 80 percent recycling and 20 percent Subtitle C landfilling by 2005.

3. RESULTS

In this section the Agency presents disposal emissions, sensitivity analyses, and net emissions for the policy options. All of the scenarios modeled are constructed as follows:

- Growth Option - We used the 2.4 percent annual growth rate from EIA.

- Mercury Content Option - We used the values specified in Section 2.1.2 and shown below:

T12 Lamps

Pre 1992	41 mg total mercury
1992 - 1996	30 mg total mercury
Post 1996	21 mg total mercury

T8 Lamps

Pre 1996	30 mg total mercury
1996 - 2000	15 mg total mercury
Post 2000	10 mg total mercury

- Lamp Use Option - We used the replacement rules defined in Section 2.1.2.

- National Disposal Option - Each National Disposal Option consists of Baseline Management from 1992 through 1997. We assumed that 1998 is the first year that the policy would be adopted. In that year the waste management flows become either CE or UW, depending upon the policy being modeled. In the Baseline case, waste management flows remain unchanged.

3.1 WASTE MANAGEMENT EMISSIONS

Table 3-1 presents the emissions by year and cumulative emissions for each of the three policy options. The UW variants sorted as expected, with UW-Moderate having the highest emissions and UW-Rapid the lowest. Because the emissions rate from recycling is higher than the emissions rate from Subtitle C landfills, the Agency expects that the increased recycling under UW-Moderate will result in increased emissions compared to UW-Gradual. Thus, we expect UW-Moderate to have higher emissions than UW-Gradual. Overall, we conclude that the absolute emissions from the disposal system are a stronger function of emissions factor estimates than policy options, while the relative difference among policy options is directly attributable to partitioning coefficients.

Disposal emissions decline about 24 percent from 1998 to 2003 under each of the options, and then increase slightly thereafter. This is attributable to the decline of mercury entering the disposal system. Reductions in the mercury content of lamps tend to offset the lamps' population growth, and hence the overall quantity of mercury declines and then stabilizes.

Table 3-1. Annual Mercury Disposal Emissions from Lamps (1998-2007) (kg)

Scenario Name	Estimate	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Total
Base Case	Central	902	881	831	755	699	683	682	682	686	694	7,495
Base Case	High	1,996	1,949	1,837	1,670	1,547	1,511	1,509	1,508	1,516	1,535	16,577
Base Case	Low	361	353	333	302	280	274	273	273	275	278	3,003
CE Option	Central	964	941	887	807	747	730	729	728	732	741	8,007
CE Option	High	2,191	2,140	2,017	1,833	1,698	1,659	1,657	1,656	1,665	1,685	18,201
CE Option	Low	410	401	378	343	318	311	310	310	312	316	3,408
UW - Gradual Option	Central	834	762	676	583	517	488	477	472	474	480	5,763
UW - Gradual Option	High	1,873	1,701	1,498	1,279	1,122	1,047	1,010	986	991	1,003	12,509
UW - Gradual Option	Low	387	340	286	228	183	150	122	95	95	96	1,982
UW - Moderate Option	Central	898	838	755	653	575	532	502	472	474	480	6,177
UW - Moderate Option	High	2,009	1,864	1,664	1,429	1,245	1,140	1,063	986	991	1,003	13,393
UW - Moderate Option	Low	389	343	289	231	185	152	123	95	95	96	1,997
UW - Rapid Option	Central	624	609	575	522	484	472	472	472	474	480	5,184
UW - Rapid Option	High	1,304	1,274	1,201	1,091	1,011	987	987	986	991	1,003	10,834
UW - Rapid Option	Low	125	122	115	105	97	95	95	95	95	96	1,040

We note that emissions are small in comparison to other anthropogenic sources of mercury. For example, the Mercury Report to Congress estimates total anthropogenic mercury emissions at approximately 220,000 kg per year, with individual source categories emitting up to 58,800 kg per year. Our estimate of annual mercury emissions from lamp disposal in the Baseline Central is on the order of 902 kg/yr in 1998.

Table 3-2 presents cumulative lamp emissions from waste management and disposal activities comprising each option. Table 3-2 shows that cumulative lamp mercury disposal emissions ranged from a high of 18,201 kg (CE-High) to a low of 1,040 kg (UW-Rapid-Low). As noted in the table, transportation and MWC emissions dominate emissions from the Baseline and CE policy options, accounting for over 60 percent of emissions from these options in the central emissions estimate case. In contrast, recycling becomes the largest source of emissions under the UW-Rapid-Central variant (about 60 percent of emissions). Under the Moderate and Gradual variants of UW, noncompliance activities again dominate emissions, with noncompliant transport and MWCs comprising over 50 percent of emissions.

3.2 SENSITIVITY ANALYSES

Because of the lack of reliable data on lamp breakage rates during transport, the Agency performed a series of sensitivity runs to judge the extent to which the estimates of lamp breakage affect the overall mercury disposal emissions estimates under the CE option. Table 3-3 summarizes the annual mercury disposal emissions rates under the CE option based on a 10 percent, 25 percent, 50 percent, and 75 percent lamp breakage rate during transport. It also shows annual mercury disposal emissions under the CE option based on 100 percent compliance.

Table 3-3 shows that the model's annual disposal emissions estimates are greatly influenced by lamp breakage rates during transport under the CE option. For example, for CE Central, the model originally assumes a 100 percent breakage rate for lamps being transported under Subtitle D Transport and CE Compliant Transport. Based in part on this assumption, the model estimates mercury disposal emissions of 964 kg under CE Central for 1998 (as shown in Table 3-1). However, if we assumed that lamp breakage is 10 percent (e.g., because best practices are being followed), the model estimates mercury disposal emissions under CE Central for 1998 to be 450 kg. This is a decrease of 514 kg (53 percent) from the model's original CE Central estimate.

The table also shows that, at 100 percent compliance, the mercury disposal emissions under the CE option are 734 kg for 1998, which is approximately 230 kg below the original CE Central estimate for 1998. (See Figure 2-2 for original compliance rates under the CE option.)

Table 3-2. Cumulative Mercury Lamp Disposal Emissions by Scenario and Activity (kg)*

Scenario Name	Disposal Activity	Central	Central Percent	High	High Percent	Low	Low Percent
Base Case							
	MWC	2,646.0	35.3%	5,083.0	30.7%	1,438.3	47.9%
	Onsite Crush -D	787.4	10.5%	1,731.2	10.4%	83.8	2.8%
	Onsite Crush-C	196.8	2.6%	432.8	2.6%	20.9	0.7%
	Recycle Baseline C	168.6	2.2%	336.2	2.0%	5.6	0.2%
	Subtitle C Landfill	56.9	0.8%	0.0	0.0%	0.0	0.0%
	Subtitle C Management	0.0	0.0%	0.0	0.0%	0.0	0.0%
	Subtitle C Transport	8.4	0.1%	41.9	0.3%	1.7	0.1%
	Subtitle D Landfill	279.9	3.7%	1,133.9	6.8%	0.1	0.0%
	Subtitle D Management	0.0	0.0%	0.0	0.0%	0.0	0.0%
	Subtitle D Transport	3,350.9	44.7%	7,818.2	47.2%	1,452.3	48.4%
		7,495.0	**100.0%**	**16,577.2**	**100.0%**	**3,002.7**	**100.0%**

* Mercury emissions are summed over 10 year period: 1998-2007

Table 3-2. Cumulative Mercury Lamp Disposal Emissions by Scenario and Activity (kg)* (continued)

Scenario Name	Disposal Activity	Central	Central Percent	High	High Percent	Low	Low Percent
CE Option							
	CE Compl. Transport	4,241.0	53.0%	9,895.0	54.4%	1,838.1	53.9%
	CE Noncomply Landfills	3.7	0.0%	16.3	0.1%	0.0	0.0%
	CE Recycle	206.1	2.6%	395.2	2.2%	69.9	2.1%
	Compliance	0.0	0.0%	0.0	0.0%	0.0	0.0%
	Compliant D Landfill	300.3	3.8%	1,318.5	7.2%	0.1	0.0%
	MWC	2,289.8	28.6%	4,395.0	24.1%	1,243.6	36.5%
	Noncompliance/CESQG	0.0	0.0%	0.0	0.0%	0.0	0.0%
	Onsite Crush -D	442.9	5.5%	973.8	5.4%	47.1	1.4%
	Onsite Crush -D/NC	49.2	0.6%	108.2	0.6%	5.2	0.2%
	Subtitle C Landfill	2.8	0.0%	0.0	0.0%	0.0	0.0%
	Subtitle D Transport-NC	471.2	5.9%	1,099.4	6.0%	204.2	6.0%
		8,007.1	**100.0%**	**18,201.4**	**100.0%**	**3,408.4**	**100.0%**

* Mercury emissions are summed over 10 year period: 1998-2007

Table 3-2. Cumulative Mercury Lamp Disposal Emissions by Scenario and Activity (kg)* (continued)

Scenario Name	Disposal Activity	Central	Central Percent	High	High Percent	Low	Low Percent
UW - Gradual Option							
	MWC	1,534.2	26.6%	2,956.5	23.6%	829.7	41.9%
	Noncompliant Transport	1,935.8	33.6%	4,000.3	32.0%	839.0	42.3%
	Subtitle C Landfill	79.6	1.4%	0.0	0.0%	0.0	0.0%
	Subtitle D Landfill	162.2	2.8%	659.5	5.3%	0.1	0.0%
	UW Compl Transport	25.3	0.4%	126.7	1.0%	5.1	0.3%
	UW Compliance	0.0	0.0%	0.0	0.0%	0.0	0.0%
	UW Crushing	264.7	4.6%	582.0	4.7%	93.9	4.7%
	UW Noncompliant Crushing	164.5	2.9%	1,000.1	8.0%	161.3	8.1%
	UW Recycle	1,596.5	27.7%	3,183.7	25.5%	52.9	2.7%
	UW Noncompliance/CESQG	0.0	0.0%	0.0	0.0%	0.0	0.0%
		5,762.9	**100.0%**	**12,508.7**	**100.0%**	**1,981.8**	**100.0%**

* Mercury emissions are summed over 10 year period: 1998-2007

Table 3-2. Cumulative Mercury Lamp Disposal Emissions by Scenario and Activity (kg)* (continued)

Scenario Name	Disposal Activity	Central	Central Percent	High	High Percent	Low	Low Percent
UW - Moderate Option							
	MWC	1,534.2	24.8%	2,956.5	22.1%	829.7	41.6%
	Noncompliant Transport	1,935.8	31.3%	4,000.3	29.9%	839.0	42.0%
	Subtitle C Landfill	50.4	0.8%	0.0	0.0%	0.0	0.0%
	Subtitle D Landfill	162.2	2.6%	659.5	4.9%	0.1	0.0%
	UW Compl Transport	25.3	0.4%	126.7	0.9%	5.1	0.3%
	UW Compliance	0.0	0.0%	0.0	0.0%	0.0	0.0%
	UW Crushing	264.7	4.3%	582.0	4.3%	93.9	4.7%
	UW Noncompliant Crushing	164.5	2.7%	1,000.1	7.5%	161.3	8.1%
	UW Recycle	2,040.2	33.0%	4,068.3	30.4%	67.6	3.4%
	UW Noncompliance/CESQG	0.0	0.0%	0.0	0.0%	0.0	0.0%
		6,177.4	**100.0%**	**13,393.4**	**100.0%**	**1,996.5**	**100.0%**

*Mercury emissions are summed over 10 year period: 1998-2007

Table 3-2. Cumulative Mercury Lamp Disposal Emissions by Scenario and Activity (kg)* (continued)

Scenario Name	Disposal Activity	Central	Central Percent	High	High Percent	Low	Low Percent
UW - Rapid Option							
	MWC	664.0	12.8%	1,279.5	11.8%	359.1	34.5%
	Noncompliant Transport	837.7	16.2%	1,731.2	16.0%	363.1	34.9%
	Subtitle C Landfill	75.0	1.4%	0.0	0.0%	0.0	0.0%
	Subtitle D Landfill	70.2	1.4%	285.4	2.6%	0.0	0.0%
	UW Compl Transport	37.7	0.7%	188.5	1.7%	7.5	0.7%
	UW Compliance	0.0	0.0%	0.0	0.0%	0.0	0.0%
	UW Crushing	393.7	7.6%	865.6	8.0%	139.6	13.4%
	UW Noncompliant Crushing	71.2	1.4%	432.8	4.0%	69.8	6.7%
	UW Recycle	3,034.5	58.5%	6,051.1	55.9%	100.5	9.7%
	UW Noncompliance/CESQG	0.0	0.0%	0.0	0.0%	0.0	0.0%
		5,184.0	**100.0%**	**10,834.1**	**100.0%**	**1,039.6**	**100.0%**

* Mercury emissions are summed over 10 year period: 1998-2007

3.3 CONCLUSION

We define net mercury emissions as disposal emissions less emissions avoided from utility boilers. Prior to proceeding, it should be noted that the Agency believes this to be a reasonable metric for choosing among policy options only if emissions avoided vary among options. We believe T8 populations to be independent of the policy options. Table 3-4 presents net mercury emissions over the baseline for the policy options. Therefore, energy savings and the resultant decrease in coal-fired emissions are believed to be independent of the policy options. Further, we can conclude that Subtitle C and D landfilling would account for minimal lamp mercury emissions under either option. This is largely because the model assumes that most lamps are broken before being landfilled. On the other hand, transportation mercury emissions are an important contributor to total mercury emissions, particularly under the CE option. We believe that virtually all lamps would be broken during transport under the CE option unless conditions are added to address releases. (Transportation, as used here, covers all handling from the time the lamp becomes spent until its receipt at the destination facility.) Taken collectively, these observations suggest that, to reduce lamp mercury emissions under either option, procedures should be established that minimize emissions during transport and/or processing (e.g., crushing) of spent lamps.

Table 3-3. Sensitivity Analysis for Lamp Breakage and Compliance under CE

Scenario Name	Estimate	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Total
Base Case	Central	902	881	831	755	699	683	682	682	686	694	7,495
Base Case	High	1,996	1,949	1,837	1,670	1,547	1,511	1,509	1,508	1,516	1,535	16,577
Base Case	Low	361	353	333	302	280	274	273	273	275	278	3,003
CE @ 10% Breakage	Central	450	439	414	376	349	341	340	340	342	346	3,737
CE @ 10% Breakage	High	929	907	855	777	720	703	703	702	706	714	7,715
CE @ 10% Breakage	Low	203	198	187	170	157	153	153	153	154	156	1,684
CE @ 25% Breakage	Central	526	514	485	441	408	398	398	398	400	405	4,373
CE @ 25% Breakage	High	1,107	1,081	1,020	927	858	838	838	837	841	852	9,199
CE @ 25% Breakage	Low	236	230	217	197	183	179	178	178	179	181	1,960
CE @ 50% Breakage	Central	654	639	602	547	507	495	495	494	497	503	5,433
CE @ 50% Breakage	High	1,405	1,372	1,294	1,176	1,089	1,064	1,063	1,062	1,068	1,081	11,673
CE @ 50% Breakage	Low	291	284	268	244	226	220	220	220	221	224	2,419
CE @ 75% Breakage	Central	782	763	720	654	606	592	591	591	594	601	6,493
CE @ 75% Breakage	High	1,703	1,663	1,568	1,425	1,320	1,289	1,288	1,287	1,294	1,310	14,147
CE @ 75% Breakage	Low	347	338	319	290	269	262	262	262	263	267	2,879
CE 100 Percent	Central	734	717	676	614	569	555	555	555	558	564	6,096
CE 100 Percent	High	1,759	1,718	1,620	1,472	1,364	1,332	1,331	1,330	1,337	1,353	14,615

Table 3-4. Net Mercury Emissions from Lamps (kg)

Scenario Name	Year	Utility Emissions Savings	Lamp Disposal Emissions: Central Tendency	Lamp Disposal Emissions: High Estimate	Lamp Disposal Emissions: Low Estimate	Net Emissions: Central Tendency	Net Emissions: High Estimate	Net Emissions: Low Estimate
Base Case								
	1998	0	902	1,996	361	902	1,996	361
	1999	0	881	1,949	353	881	1,949	353
	2000	0	831	1,837	333	831	1,837	333
	2001	0	755	1,670	302	755	1,670	302
	2002	0	699	1,547	280	699	1,547	280
	2003	0	683	1,511	274	683	1,511	274
	2004	0	682	1,509	273	682	1,509	273
	2005	0	682	1,508	273	682	1,508	273
	2006	0	686	1,516	275	686	1,516	275
	2007	0	694	1,535	278	694	1,535	278
		0	**7,495**	**16,577**	**3,003**	**7,495**	**16,577**	**3,003**
CE Option								
	1998	0	964	2,191	410	964	2,191	410
	1999	0	941	2,140	401	941	2,140	401
	2000	0	887	2,017	378	887	2,017	378
	2001	0	807	1,833	343	807	1,833	343
	2002	0	747	1,698	318	747	1,698	318
	2003	0	730	1,659	311	730	1,659	311
	2004	0	729	1,657	310	729	1,657	310
	2005	0	728	1,656	310	728	1,656	310
	2006	0	732	1,665	312	732	1,665	312
	2007	0	741	1,685	316	741	1,685	316
		0	**8,007**	**18,201**	**3,408**	**8,007**	**18,201**	**3,408**

Table 3-4. Net Mercury Emissions from Lamps (kg) (continued)

		Utility Emissions	Lamp Disposal Emissions			Net Emissions		
Scenario Name	**Year**	**Savings**	**Central Tendency**	**High Estimate**	**Low Estimate**	**Central Tendency**	**High Estimate**	**Low Estimate**
UW - Gradual Option								
	1998	0	834	1,873	387	834	1,873	387
	1999	0	762	1,701	340	762	1,701	340
	2000	0	676	1,498	286	676	1,498	286
	2001	0	583	1,279	228	583	1,279	228
	2002	0	517	1,122	183	517	1,122	183
	2003	0	488	1,047	150	488	1,047	150
	2004	0	477	1,010	122	477	1,010	122
	2005	0	472	986	95	472	986	95
	2006	0	474	991	95	474	991	95
	2007	0	480	1,003	96	480	1,003	96
		0	**5,763**	**12,509**	**1,982**	**5,763**	**12,509**	**1,982**
UW - Moderate Option								
	1998	0	898	2,009	389	898	2,009	389
	1999	0	838	1,864	343	838	1,864	343
	2000	0	755	1,664	289	755	1,664	289
	2001	0	653	1,429	231	653	1,429	231
	2002	0	575	1,245	185	575	1,245	185
	2003	0	532	1,140	152	532	1,140	152
	2004	0	502	1,063	123	502	1,063	123
	2005	0	472	986	95	472	986	95
	2006	0	474	991	95	474	991	95
	2007	0	480	1,003	96	480	1,003	96
		0	**6,177**	**13,393**	**1,997**	**6,177**	**13,393**	**1,997**

Table 3-4. Net Mercury Emissions from Lamps (kg) (continued)

Scenario Name	Year	Utility Emissions Savings	Lamp Disposal Emissions			Net Emissions		
			Central Tendency	High Estimate	Low Estimate	Central Tendency	High Estimate	Low Estimate
UW - Rapid Option								
	1998	0	624	1,304	125	624	1,304	125
	1999	0	609	1,274	122	609	1,274	122
	2000	0	575	1,201	115	575	1,201	115
	2001	0	522	1,091	105	522	1,091	105
	2002	0	484	1,011	97	484	1,011	97
	2003	0	472	987	95	472	987	95
	2004	0	472	987	95	472	987	95
	2005	0	472	986	95	472	986	95
	2006	0	474	991	95	474	991	95
	2007	0	480	1,003	96	480	1,003	96
		0	**5,184**	**10,834**	**1,040**	**5,184**	**10,834**	**1,040**