Mercury Lamp

Drum-Top Crusher

Study

Mercury Lamp Drum-Top Crusher Study

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DTC Study Team
Paul Abernathy, ALMR
Catherine Bodurow, National Academy Institute of Medicine
Noah Borenstein, EPA Region 3
Alexis Cain, EPA Region 5
Stephen Coffee, CIH, Booz Allen Hamilton
Cathy Davis, EPA Office of Solid Waste
Suzanne Davis, California EPA Department of Toxic Substance Control
Mark Hanrahan, Booz Allen Hamilton
Greg Helms, EPA Office of Solid Waste
Jordan Murphy, Booz Allen Hamilton
Wayne Naylor, EPA Region 3
Tad Radzinski, EPA Region 3
Betty Ann Quinn, EPA Region 3
John Wesnousky, California EPA Department of Toxic Substance Control

Lamp Crushing Facilities
AERC Recycling Solutions
Earth Protection Services, Inc.

Equipment Manufacturers
Rick Beierwaltes, Air Cycle Corporation
Scott Beierwaltes, Air Cycle Corporation
Edward Domanico, Hazardous Material Specialist
David Dougall, Dextrite, Inc.
Albert Greene, Dextrite, Inc.
Don Seiler, Resource Technology, Inc.
Mike Seiler, Resource Technology, Inc.

Philips Lighting
Steve McGuire, Philips Lighting

Peer Reviewers
Dr. Carl Hebrandson, Minnesota Department of Health
Dr. Steven Lindberg, Oak Ridge National Laboratory
Michael McLinden, CIH, New Jersey Department of Environmental Protection

ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
ANOVA	Analysis of Variance
cc/min	Cubic Centimeters per Minute
DTC	Drum Top Crusher
EFT	Extended Field Test
EFTS	Extended Field Test Study
EPA	Environmental Protection Agency
EPSI	Earth Protection Services, Inc.
Hg	Mercury
LOEL	Lowest Observed Effect Level
MCE	Mixed Cellulose Ester
mg	Milligrams
mg/m^3	Milligrams per Cubic Meter
min	Minutes
mm	Millimeters
NA	Not Applicable
ND	Not Detected
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PPE	Personal Protective Equipment
PVS	Performance Validation Study
RCRA	Resource Conservation and Recovery Act
REL	Recommended Exposure Limit
RfC	Reference Concentration
TLV	Threshold Limit Value
TSDF	Treatment, Storage, and Disposal Facility
TWA	Time Weighted Average
μg	Microgram

1. EXECUTIVE SUMMARY

The increasingly wide-spread use of energy-efficient, fluorescent lamps has had tremendous environmental benefits. However, mercury, a toxic chemical, is an essential component of fluorescent lamps. When lamps are broken, whether during storage, transport, disposal, or crushing, a substantial portion of the mercury contained in the lamp is released as mercury vapor. If the mercury vapor is not controlled or contained, it could be readily inhaled by anyone in the area and be hazardous to the health of those exposed individuals. Additionally, mercury released from broken lamps is persistent in the environment, where it can be chemically transformed to methylmercury, which is more toxic than elemental mercury and which bioaccumulates up the food chain.

When lamps are disposed of in a landfill, rather than recycled, a substantial percentage of the lamps are broken and virtually all of the mercury contained in the lamps is released into the environment. In addition, lamps may be broken during collection, shipping, or handling. Therefore, in order to protect human health and the environment, the Environmental Protection Agency (EPA) strongly encourages the safe handling and recycling of fluorescent lamps.

Lamp recycling can be done either by sending whole, boxed lamps to a recycler or by using a drum top crusher (DTC) device at the point where lamps are removed from service. DTC devices are designed to fit on the top of a 55 gallon drum in order to prevent the release of mercury vapors while crushing the fluorescent lamps into the drum below. These devices are used to reduce the volume of waste lamps so as to improve storage and handling and reduce shipping costs associated with fluorescent lamp recycling. Each method of recycling has potential benefits and draw-backs. This report examines DTC devices only and does not address whole lamp recycling or disposal of lamps.

As part of ongoing efforts to encourage safe management of mercury-containing equipment and fluorescent lamps, EPA conducted the Mercury Lamp Drum-Top Crusher Study (the Study). The objective of the Study was to evaluate the ability of four DTC devices to contain the mercury released from crushed lamps in terms of preventing worker exposure to adverse levels of airborne mercury resulting from the operation of these devices. The scope of the Study did not include evaluating other lamp handling methods or comparing other lamp handling methods to the use of DTC devices. This report presents the findings of the Study; the purpose of this report is not to endorse or discourage the use of DTC devices.

1.1 Study Overview

The original study design called for testing of four DTC devices from four different manufacturers: A, B, C, and D.[1] However, the Manufacturer D device was removed from the Study after two rounds of testing because of its inability to maintain

[1] *The focus of the Study was on DTC devices in general. It was not the intent of the study team to find the "best" manufacturer or to recommend a certain device. The manufacturers that participated in the Study may choose to identify themselves; however, for the purposes of this report, Manufacturer A, B, C, and D will not be identified.*

mercury vapor concentrations below the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) of 0.1 milligrams per cubic meter (mg/m^3) during device operation (*refer to Section 3.5.3 and Appendix I*). Therefore, the executive summary focuses primarily on the three other DTC devices that completed the entire Study. A large amount of data was collected and analyzed throughout the Study. To fully understand the information gained, this report should be reviewed in its entirety.

Testing of the DTC devices was performed in a confined space, constructed for the Study, at three separate commercial lamp recycling facilities (the AERC Recycling Solutions facility in Ashland, VA, was used twice during the Study). Lamp recycling facilities were used as the sites for the Study to ensure compliance with all state requirements, to take advantage of the availability of spent lamps that were sent to them for recycling, and to facilitate appropriate recycling of the lamps crushed during the Study. The containment structure was used in order to isolate the Study from background mercury present in the facilities due to regular lamp recycling operations (*refer to Sections 4.2 and 6.1 for information about background mercury levels*) and also to test a "worst-case" scenario for the type of environment in which a DTC device may be operated (i.e., a room with low ventilation rates). Operator exposures would be expected to be lower than found in this Study if a DTC device is operated in a room with higher ventilation rates than used in this Study.

Concentrations of mercury in the air were measured using two Jerome Mercury Vapor Analyzers (Jerome analyzers) and using National Institute for Occupational Safety and Health (NIOSH) Analytical Method N6009 and Draft Analytical Method N9103 (*refer to Appendix E*). Surface wipe samples (from the inside of the containment structure), unbroken lamps, and bulk samples of crushed lamps and pollution control media were also collected and analyzed for mercury using procedures described in Appendix E. A number of observations about possible mercury exposure, DTC operation, and operational problems with the devices tested were made based on data collected over a range of conditions, including:

- Operational period – normal crushing
- Operational period – drum changes and filter changes
- Operational period – improper assembly/leakage of seals
- Non-operational period – broken lamps staged for crushing
- Non-operational period – overnight (full, or partially-full, 55-gallon drum)

After the Study was completed, each manufacturer was able to review the results specific to their device. The purpose of this was to make it possible for the manufacturers to consider the results of the Study and make any modifications to their devices based on these results.

In September 2004, EPA prepared a draft report for the Study, and RTI International, under contract to EPA, arranged for an independent review of the draft report, by recognized technical experts. This review was conducted by letter format in a manner consistent with EPA's Office of Research and Development and Science Policy Council *Peer Review Handbook* (December 2000). Many substantive comments

were made by the reviewers. As a result of these comments, EPA extensively revised this report (*refer to Appendix J for the peer review comments and EPA's responses to the comments*).

1.2 Observations

All three of the devices that completed the Study usually maintained mercury levels below the OSHA PEL within the containment structure and in the operator breathing zone, and one device generally maintained mercury levels below the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) of 0.025 mg/m^3 during normal lamp crushing operations.[2] However, this Study also demonstrated that during operation of a DTC device, under the operating conditions that existed during the Study, the operator can be exposed to levels of mercury above the TLV and the PEL. Specifically:

- Operator exposure only remained below the OSHA PEL and ACGIH TLV values when the three well-designed DTC devices were operated optimally. That is, when a sub-standard device was used, and when the well-designed devices were not performing optimally or were improperly assembled, operator exposures increased above these levels. (Note: In most of the cases of potential mercury exposure experienced in this Study, the operator only realized that the device being used was not effectively containing mercury because a real-time mercury vapor monitor, equipped with an alarm, was used. The exception to this was that when one of the DTC devices was incorrectly assembled and was, therefore, releasing much more mercury than it would have under normal operating conditions, the operator noted white powder coming out of the connection between the feed tube and the main device assembly that was missing a seal.)

- Measurable concentrations of mercury were detected in the air in the lamp recycling facilities (background air sample results ranged from 0.00052 mg/m^3 to 0.044 mg/m^3).

- There is an increased risk of mercury exposure when full drums are replaced with empty ones, an operation inherent in the use of a DTC device. Drum changes typically resulted in short-term excursions above the PEL. These high mercury levels decreased after the drum changes were complete. Several short-duration, high-volume air samples were taken during drum changes to estimate maximum possible worker exposure. Over 70 percent of these samples were above the PEL.

- Performance of DTC devices may change over the lifetime of the device and under varying environmental conditions. Two of the devices showed a significant

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[2] *Throughout this report the ACGIH TLV is used as a point of reference with which the analytical air samples are compared. The TLV is an eight-hour, time-weighted average; however, the analytical air samples generally represent one to three hour sampling periods (refer to Section 3.1 for a description of the analytical air samples and Appendix A, Table 1 for individual sample durations). Sample results that are greater than the TLV should not necessarily be interpreted to indicate that use of one of the DTC devices included in the Study would result in operator exposure above the TLV because exposure would need to be averaged over an eight-hour day and a 40-hour week.*

decrease in their ability to contain mercury after being used to crush eight drums of lamps. (Note that changes in the test environment, such as increased ambient temperature, may have had some affect on device performance.)

- Minor mistakes in assembly of a DTC device can significantly affect its ability to capture mercury. A leak on one device notably raised mercury levels for the samples in the operator's breathing zone and caused mercury concentrations to exceed the PEL for the area sample collected near the leak. The leak was located at one of the seals and was due to improper device assembly.

- Overnight tests, which were performed during non-operational periods, were inconclusive. Further study would be needed to determine whether or not drums containing crushed lamps with the DTC device attached to the top of the drum, but not in operation, would release mercury in quantities that pose a risk.

- Finally, in one test, the operation of the Manufacturer D device resulted in ambient mercury concentrations of 0.89 mg/m^3, nine times the OSHA PEL, even though exclusively low mercury, Alto® lamps, manufactured by Phillips Lighting, were used.[3] The results from this test illustrate that mercury vapor can exceed established levels even if the lamps being crushed in the DTC device (i.e., low-mercury lamps) are not identified as hazardous wastes.

Use of DTC devices allows several hundred crushed lamps to occupy the space that 40 or 50 whole lamps would occupy, thereby reducing storage and shipping costs. This leads to a reduction in recycling costs on a per-lamp basis. Crushing lamps before shipment also has the advantage of allowing the lamps to be shipped to the recycler in a well-sealed, durable container that is unlikely to release substantial amounts of mercury. Shipping whole lamps inevitably leads to some breakage and potential release; with careful handing, the amount of breakage can be reduced.

The DTC devices evaluated as part of this Study all released some mercury when used. The mercury released during DTC device use will create certain new mercury exposure situations. Exposure will be experienced by the DTC device operator and any assistants handling lamps or working directly with the DTC device. Less direct mercury exposures that could be created by DTC device use include anyone working in or visiting buildings in which DTC devices are used. To eliminate these unnecessary indirect mercury exposures, the ventilation of the lamp crushing room would need to be separate from the general building ventilation system, as is done at industrial lamp recycling facilities.

Additional findings regarding the design and operation of DTC devices, and future areas of study, are discussed in Chapter 7.

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[3] *The Alto® lamps typically contain three to five mg of mercury per lamp and are advertised as "TC compliant" by the manufacturer, meaning that the lamps would generally not be classified as hazardous waste when discarded.*

2. SCOPE OF STUDY

2.1 Mercury Fluorescent Lamp Disposal

On May 11, 1995, EPA adopted new streamlined hazardous waste management regulations under the Resource Conservation and Recovery Act (RCRA) governing the collection and management of certain widely generated hazardous wastes termed "universal wastes" (60 FR 25491). The new hazardous waste management regulations were designed to facilitate the environmentally-sound collection and proper management of certain hazardous waste batteries, pesticides, and mercury-containing thermostats. Hazardous waste lamps were added to the federal list of universal wastes on January 6, 2000 (64 FR 36465). On August 5, 2005, the category of mercury-containing thermometers was removed from the federal list, and a broader category, mercury-containing devices, was added to the federal list of universal waste (70 FR 45508).[4] The universal waste regulations are set forth in 40 CFR Part 273.

By introducing flexibility into the storage, transport, and collection of universal hazardous wastes, the universal waste rule seeks to encourage the development of programs to reduce the quantity of hazardous wastes going to municipal solid waste landfills or combustors and to assure that wastes subject to the universal waste system go to appropriate hazardous waste recycling facilities or treatment, storage and disposal facilities (TSDF). Handlers of universal wastes are subject to more flexible standards for storing, transporting, and collecting these wastes than under full Subtitle C regulation. Hazardous waste lamps are regulated as a universal waste in order to encourage lamp recycling, facilitate better lamp management, and improve compliance with the hazardous waste regulations.

2.2 Study Overview

The Study was performed at three different existing, large-scale lamp recycling facilities. Four DTC devices were originally included in the Study, but only three of the devices completed the Study (*refer to Section 3.5.3*). Analytical air samples were collected to quantify mercury concentrations inside the containment structure and operator exposure to mercury, and a Jerome Mercury Vapor Analyzer was employed to provide real-time measurements of ambient mercury vapor concentrations. Additional samples were collected for the Mass Balance Study.

2.2.1 Study Location

The Study was conducted at mercury lamp recycling facilities for a number of reasons. One critical reason was that these facilities are permitted for hazardous waste lamp processing. Because some states require permits for the use of a DTC device, reliance on the facilities' existing permits allowed the Study to be conducted more quickly and inexpensively and was a key factor in the decision to fund and

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[4] *Mercury-containing thermometers are a type of mercury-containing devices, and thus, are still included in the federal list of universal waste under the broader category.*

conduct the Study. The lamp recycling facilities also provided sufficient numbers of fluorescent lamps to complete each phase of the Study, as well as valuable assistance by receiving and storing the DTC devices, providing sufficient space to conduct the Study, and recycling the crushed lamps generated in the course of the Study.

The disadvantage of conducting the Study at lamp recycling facilities was that each facility had existing background concentrations of mercury that could potentially confound study results. The detected background concentrations are presented in Section 4.2, and apparent effects on study results are further discussed in Section 6.1.

In each facility, the office space was segregated from the work area for the industrial lamp crushing activities. However, the facility layout was different at each study location, which affected facility background mercury levels. AERC Ashland had two large bays, one of which housed an industrial lamp crusher while the other bay was used for the Study. A large doorway separating the two bays was kept closed for most of the study duration. This allowed the DTC crushing activities to be isolated from direct mercury emission sources, but fugitive emissions from the industrial recycling operations were present in the bay used for the Study. AERC Melbourne provided an isolated bay for the Study, and the door between this bay and the main bay where AERC operations took place was closed for the duration of the Study. At EPSI Phoenix, the Study was conducted in the same bay as the facility's industrial-size lamp crusher, resulting in somewhat higher mercury background concentrations, as compared to the other test sites (refer to Sections 4.2 and 6.1).

2.2.2 Containment Structure

During the Study, the DTC devices were operated inside a fabricated containment structure. This structure provided a "worst case" environment in which to evaluate the performance of each device by minimizing ventilation and containing mercury emissions in an enclosed space.[5] The structure was also intended to isolate the DTC operations from the background mercury present in the lamp recycling facilities, although it did so only to a limited extent. The containment structure consisted of a frame constructed from ¾ inch PVC tubing and covered with a single layer of four-millimeter (mm) thick polyethylene sheeting on the walls, floor, and ceiling (*refer to Photograph 2. 1, Photograph 2. 2, Photograph 2. 3, and Photograph 2. 4*).[6]

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[5] *Operator exposures would be expected to be lower than found in this Study if a DTC device is operated in a room with higher ventilation rates than used in this Study.*

[6] *Mercury has been shown to sorb onto and permeate through polyethylene. Another material, such as vinyl, may have been more appropriate for this Study. During the first set of tests in Ashland, VA, the measurements of the containment structure were 12 feet (ft.) by 12 ft. by 10 ft. high to ensure that there was adequate space to operate each device properly. The containment structure ceiling height was lowered to 8 ft. in Phoenix, AZ, to expedite test set-up. However, three of the devices had feed chutes angled upward, and, as lamps were being fed into the device, they scraped against the ceiling of the containment area. Therefore, containment structures measuring 10 ft. in height were utilized in Melbourne, FL, and the second set of tests in Ashland, VA.*

Photograph 2. 1: AERC Ashland Facility – Containment Structure – First Visit

Photograph 2. 2: EPSI Phoenix Facility – Containment Structure

Photograph 2. 3: AERC Melbourne Facility – Containment Structure

Photograph 2. 4: AERC Ashland Facility – Containment Structure – Second Visit

The polyethylene walls, floor, and ceiling were changed before testing each device at each location. The containment structure used a "flap" door to allow entry and exit by the operators. This door, which overlapped the walls, limited the amount of air exchanged between inside and outside the containment structure; however, it was not possible to entirely eliminate air exchanges.

In the initial parts of the Study, the polyethylene was measured and cut inside the facility, next to the containment frame. This was done during Phase I of the Performance Validation Study in Ashland, Virginia and in the first Extended Field

Test in Phoenix, Arizona. However, results from the pre-test wipes of surfaces within the containment structure (taken prior to crushing any bulbs in the DTC device) indicated that mercury was detected on the polyethylene sheeting (*refer to Appendix A*, *Table 2*). The field team determined that the mercury contamination on the sheeting was most likely attributable to measuring and cutting the polyethylene on the contaminated floor inside the recycling facility, as well as deposition of background airborne mercury from ongoing facility operations. To reduce the potential for contaminating the polyethylene sheeting during construction of the containment structure, staging areas for measuring and cutting the polyethylene sheets were established in the parking lot outside the facility for the second Extended Field Test in Melbourne, Florida and used for all of the remaining tests.

2.2.3 General Procedures

At each stage of the Study, the DTC devices were generally operated in conformance with the manufacturer's operating manual. The only deviation from the operating manual was that more lamps than recommended by one manufacturer (Manufacturer C) were crushed during each round of the Extended Field Test Study.[7] DTC device operations included device assembly and placement on the drum, routine lamp crushing operations, and drum and filter changes. When the DTC device manufacturer representatives were available and on-site, they were allowed to provide further operational instructions specific to their device. In the first phase of the Performance Validation Study, representatives of the four manufacturers were required to be present during the operation of their device. For the remainder of the Study, DTC device representatives were invited to observe, but their presence was not required to include their device in the Study.

Each DTC device was operated according to the following procedure:

1. Construct the containment structure (*described in Section 2.2.2*);

2. Calibrate the Jerome analyzer and take background readings;

3. Equip the operator with required personal protection equipment (PPE), Tyvek® coveralls, respirator, Kevlar® gloves, etc., and personal air samplers;

4. Assemble the DTC device on top of the collection drum inside the containment structure;

5. Ensure that the device is properly assembled and the filter is in place;

6. Collect pre-test wipe samples.

7. Bring spent lamps into the containment structure;

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[7] *The operator's manual for the Manufacture C device specifies that the device should only be used to crush one drum of lamps per eight-hour period in order meet with OSHA safety standards.*

8. Power up the device (runs off of 110-volt, single-phase service) and ensure negative pressure inside the device has been activated;

9. Begin feeding lamps (feed rate during the test was between 30 and 40 bulbs per minute using a two-person crew; for a one-person crew, the rate is expected to be closer to 20 to 25 bulbs per minute).

10. After filling the prescribed number of drums, collect post-test wipe samples from the device and from the walls, ceiling, and floor of the containment structure.

The specific methodologies employed during each of the three studies are discussed in detail in Chapter 3 of this report.

2.2.4 Study Components

The DTC Device Study was divided into three distinct studies.[8] The basic elements of each study are described below.

- Performance Validation (PVS) – sought to (1) quantify ambient mercury vapor concentrations inside the containment structure and personnel exposure during the operation of several DTC devices, and (2) establish initial baseline air concentrations of mercury (Phase I) for comparison to air concentration measurements after DTC devices have processed enough fluorescent lamps to fill approximately eight 55-gallon drums (Phase II).

- Mass Balance Study – sought to estimate the overall capture efficiency of each device by quantifying (1) the total mass of mercury contained in the lamps fed into the DTC device, and (2) the masses of mercury retained in the drum, captured by the DTC device's pollution control equipment, and released into the ambient environment as mercury vapors, aerosols, and particulates containing mercury. Samples for the Mass Balance Study were collected during Phase I of the PVS.

- Extended Field Test Study (EFTS) – sought to quantify and compare ambient mercury concentrations and worker exposure during the operation of the different DTC devices at several different locations, which represented a range of potential operating conditions. The EFTS was designed to evaluate the mercury vapor capture efficiency of each DTC device in a simulated occupational environment, with a focus on assessing the potential for human (operator) exposure to mercury as a result of DTC use. The following tests were performed as additional components to the EFTS.

  – Overnight Test – was conducted during EFT #1, EFT #2, and EFT #3 and sought to quantify the amount of mercury that may escape the DTC device and full drum assembly when the device is not in operation.

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[8] *Because of the exploratory nature of the Study and the desire to maximize data collection while in the field, certain ad hoc changes to the original sampling plan were introduced not always with the ability to pre-define data quality objectives such as sample sizes or acceptable error ranges.*

– "U" Shaped Lamp Test – was conducted during EFT #3 and sought to evaluate airborne mercury levels from two DTC devices, while processing "U" shaped lamps (U-tubes).

– Box Test – was conducted during EFT #2 and EFT #3 and sought to determine the degree to which shipping boxes containing broken lamps located inside the containment structure contributed to elevated mercury concentrations detected during early phases of the DTC Study.

2.2.5 Equipment

The DTC Device Study evaluated crushers from four different manufacturers:

- Manufacturer A *(Photograph 2. 5)*
- Manufacturer B *(Photograph 2. 6)*
- Manufacturer C *(Photograph 2. 7)*
- Manufacturer D *(Photograph 2. 8)*

All manufacturers except Manufacturer A provided new, unused DTC devices for the Study. Manufacturer A provided a prototype machine that was used prior to the Study, but was cleaned and decontaminated by the manufacturer before it was sent for testing in the Study. For reasons that are discussed in Section 3.5.1 of this report, the Manufacturer D device was tested only during Phase I of the PVS and the first round of the EFTS.

Photograph 2. 5: Manufacturer A Device

Photograph 2. 6: Manufacturer B Device

Photograph 2. 7: Manufacturer C Device

Photograph 2. 8: Manufacturer D Device

Table 2. 1 summarizes the manufacturer information contained in the operating manual that was provided with each machine.

Table 2. 1: DTC Device Equipment Operating Manual Comparison

	Manufacturer A	Manufacturer B	Manufacturer C	Manufacturer D
Filter Maintenance Change Frequency				
Particulate Filter	Change every 100,000 Lamps	Change Every 2,400 Lamps	Change Every Full Drum	Change Every 300 Lamps
HEPA Filter	NA	NA	Change Every 10 Drums	Change Every 10 Particulate Filters or 3,000 Bulbs
Carbon Filter (quantity)	85 lbs	Not Specified (Approx. 13 oz)	22 lbs	Not Specified (Approx. 5 lbs)
Filter Change Frequency	Change After 750,000 Lamps	Change Every 2,400 Lamps. Lamp Counter Shuts Down Motor at Lamp Count of 2,400	No Change Frequency Specified	Change Annually or Every 10,000 Lamps
Operating Manual has Filter Change Instructions or Procedure For:	Particulate and Carbon Filter	Filter Cartridge (Contains Particulate and Carbon)	Particulate and HEPA Filter	Particulate, HEPA and Carbon
Operating Manual has a Log Form to Document Filter Maintenance	No	No	Yes	No
Health and Safety				
Operating Manual Specifies Operational Time Limits	No	No	Do not crush more than one drum per Eight-Hour Shift	No
Operating Manual Requires/Recommends Respirator	Required If indicated by Direct Reading Mercury Vapor Instrument Results	No	No	Required (Half Face Respirator)
Operating Manual Requires/Recommends Safety Glasses	Required	Required	Required	Required

	Manufacturer A	Manufacturer B	Manufacturer C	Manufacturer D
Operating Manual Requires/Recommends Gloves	Recommended	No	Required	Required
Operating Manual Requires/Recommends Hearing Protection	Recommended	No	No	No
Operating Manual Requires/Recommends Coveralls	Required	No	No	No
Operating Manual Requires/Recommends Air Monitoring for Mercury Vapor	Recommended	No	No	No
Operation				
Operating Manual has Equipment Operating Instructions or Procedure	Yes	Yes	Yes	Yes
Operating Manual has Shutdown Instructions or Procedure	Yes	Yes	Yes	Yes
Operating Manual Shutdown Instructions or Procedure Requires use of Vacuum System During Equipment Shutdown	Automatic Operation of Vacuum System Continuously while Device is attached to Drum of Crushed Lamps	Manually Allow Disposer to Run for 2 to 3 Minutes When Finished Using Machine	Automatic Purge for 10 Seconds after Shutdown	NA
Operating Manual has Drum Change Instructions or Procedure	Yes	Yes	No	Yes
Features and Controls				
Device Has a Drum Full Indicator	Yes	No	Yes	No
Device has Automatic Lamp Counter	No	Yes - Shuts Down Motor and provides Audible and Visual Alarm at 800 Count	No	No
Device has Lid Open Indicator/Interlock	Yes Indicator with Interlock to Prevent Motor Start	No	Yes Indicator with Interlock to Prevent Motor Start	No
Device has Programmable Logic Controller (PLC)	Yes	No	No	No
Device has Emergency Stop Switch	Yes – Crushing head will not engage unless negative pressure system is operating	No	Yes	No
Listed Lamp Capacity	400- 500 Lamps (T8 or T12 type)	800 Four-Foot Lamps	NA	1200 Four-Foot Lamps
Mercury Hazard Information				
Operating Manual Contains Mercury Hazard Information and Reference To OSHA Mercury Exposure Limits	Mercury Hazard	NA	Mercury Hazard	Mercury Hazard OSHA
Regulatory Information				

	Manufacturer A	Manufacturer B	Manufacturer C	Manufacturer D
Operating Manual Provides Information on Universal Waste	Yes	No	Yes	Yes
Operating Manual Provides Information on Lamp Recycling	Yes (Minimal)	No	Yes (Comprehensive)	Yes
Operating Manual Identifies Spent Pollution Control Media as Hazardous Waste	Specified for Filter and Carbon	Not Specified	Specified for Spent Particulate and HEPA Filters Only	Specified for Particulate, HEPA, and Carbon Filter
Operating Manual Provides Disposal Instructions for Spent Pollution Control Media	General Instruction	General Instruction	Place in Drum for Disposal with Crushed Lamps	Not Specified
Air Emissions				
Operating Manual Contains a Statement about the Device's Ability to Control Mercury Emissions	Yes "…is equipped with state of the art components to capture mercury vapors generated by crushing lamps to ensure a safe environment surrounding your drum top crusher."	No	Yes "…will remove virtually all airborne powder and mercury vapor (well over 99%)."	Yes "Crushes any length of fluorescent lamp in seconds into fragments while recovering 100% of the hazardous mercury vapors."

2.3 Testing Locations and Study Chronology

The Study was conducted at three locations over approximately five months. Table 2. 2 provides the order in which the devices were tested at each location. The following is a chronology of the DTC Device Study:

- Performance Validation Study, Phase I, AERC Recycling Solutions facility in Ashland, Virginia (AERC Ashland), from February 24, 2003 through February 28, 2003.

- Mass Balance Study, AERC Recycling Solutions facility in Ashland, Virginia (AERC Ashland), from February 24, 2003 through February 28, 2003.

- Extended Field Test Study, Test #1, Earth Protection Services, Inc. (EPSI) facility in Phoenix, Arizona (EPSI Phoenix), from March 24, 2003 through March 28, 2003.

- Extended Field Test Study, Test #2, AERC Recycling Solutions facility in Melbourne, Florida (AERC Melbourne), from April 28, 2003 through May 2, 2003.

- Extended Field Test Study, Test #3, AERC Recycling Solutions facility in Ashland, Virginia, from June 9, 2003 through June 13, 2003.

- Performance Validation Study, Phase II, AERC Recycling Solutions facility in Ashland, Virginia, from June 9, 2003 through June 13, 2003.

Table 2. 2: Order of Device Testing for DTC Device Study

Study	Date	Device
Performance Validation I	2/26/2003	C
	2/27/2003	A
	2/27/2003	D
	2/28/2003	B
Extended Field Test #1	3/24/2003	A
	3/25/2003	B
	3/26/2003	D
	3/27/2003	C
Extended Field Test #2	4/29/2003	B [a]
	4/30/2003	C
	5/1/2003	A
	5/2/2003	B [a]
Extended Field Test #3 & Performance Validation II	6/10/2003	A
	6/11/2003	B
	6/12/2003	C

a The device from Manufacturer B was tested twice during EFT #2. Refer to Section 3.5.1.

3. DATA COLLECTION METHODOLOGY

This chapter describes the procedures used to collect the various study samples, including descriptions of sampling and analysis methods and sample locations. Airborne mercury was tested using two methods:

- Analytical Air Samples – known quantities of air drawn through collection media designed to capture airborne mercury particulates and mercury vapor over extended periods of time and

- Jerome Analyzer Measurements – direct reading air samples of ambient mercury concentrations using the Jerome Mercury Vapor Analyzer.

Air samples were collected in the operator's breathing zone during normal operation, filter changes and drum changes, and in selected locations within the containment structure. Jerome measurements were taken both inside and outside the containment structure. Photograph 3. 1 shows the air sampling pump and Jerome analyzer inside the containment structure.

Photograph 3. 1: Air Sampling Pumps and Jerome Mercury Vapor Analyzer

Several additional types of samples were collected for the Mass Balance Study.

- Wipe samples – Wipes of surfaces inside the containment structure were taken to characterize the amount of mercury deposited due to DTC device operation.

- Crushed lamps – Samples were taken out of a full drum after crushing operations (approximately eight inches deep into the drum).

- Pollution control media – Bulk samples were taken of the pollution control media (HEPA filter, pre-filter, and carbon filter) of each DTC device.

- Whole lamps – Samples of the spent, unbroken, Phillips Alto® lamps were taken.

The sample collection methodology, sample analysis, and sampling locations are discussed below. Section 3.1 describes the analytical air samples collected for the Performance Validation Study (PVS), including air samples used in the Mass Balance Study, and the Extended Field Test Study (EFTS). Section 3.2 describes the Jerome

analyzer samples for the PVS and the EFTS. Section 3.3 details the methodology used for collecting the bulk samples used in the Mass Balance Study. Section 3.4 addresses the methodology for measuring surface contamination using wipe samples. Finally, Section 3.5 describes modifications and deviations to the test protocol based on operational difficulties encountered during testing.

3.1 Analytical Air Samples

Personal and area air samples were collected at numerous locations at each facility to support different aspects of the Study. The personal air samples were collected from the operator's breathing zone during operation and during drum changes, and the area samples were collected near the feed tube and the exhaust. Background samples and overnight samples were also collected.

Air samples were collected and analyzed, to measure airborne mercury concentrations in the aerosol and vapor phases, in accordance with the National Institute for Occupational Safety and Health (NIOSH) draft Analytical Method N9103[9] and NIOSH Analytical Method N6009,[10] respectively. The air samples were collected by drawing a known volume of air through two different media specific to the collection of mercury in each phase. A 37mm mixed cellulose ester (MCE) filter was first in line to capture mercury aerosols, and a Hydrar solid sorbent tube was second in line, attached to the MCE filter, to capture mercury vapors. The reporting limit for both the MCE filter and the Hydrar tube is 0.01 µg /sample. This reporting limit is based on the lowest calibration standard analyzed at the laboratory.

Air samples were collected by drawing known volumes of air through the sampling media using Sensidyne GilAir 5RC air sampling pumps equipped with multi-flow adapters (*refer to Photograph 3. 2*).

Photograph 3. 2: Sensidyne Air Sampling Pumps

The Sensidyne pumps were calibrated on site both before and after use, according to the manufacturers' specifications, using the BIOS DC-Lite calibrator as a primary standard. The calibration data are contained in Appendix B. During calibration, the

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[9] *At the time of this Study, Method N9103 (refer to Appendix E) was in draft form. It is undergoing approval by NIOSH.*

[10] *NIOSH Manual of Analytical Methods, 4th ed., Method N6009, Issue 2, 1994. A copy can be found in Appendix E.*

airflow was adjusted in order to establish a known flow rate. The flow rates of the pumps varied depending on sample type. Ranges of pump flow rates are listed below in cubic centimeters per minute (cc/min).

- Background Samples: 136 – 221 cc/min
- On Operator, During Drum Filling: 135 – 212 cc/min
- On Operator, Filter Changes and Drum Changes:[11] 154 – 261 cc/min
- On Operator, Ceiling Samples: 247 – 260 cc/min
- At Exhaust of the Device: 121 – 253 cc/min
- At Feed Tube of the Device: 125 – 210 cc/min
- Overnight Samples: 100 – 163 cc/min

At each facility, three sets of laboratory blanks were prepared at the beginning of each study. Three MCE filters and three Hydrar-sorbent tubes were labeled and placed in storage in the calibration room. Two sets of field blanks were prepared for each day of sampling at each location. Two MCE filters were labeled, the caps were opened and replaced, and the filters were placed into storage in the calibration room. Two Hydrar-sorbent tubes were labeled, the ends of the tubes were broken and capped, and the tubes were placed into storage in the calibration room.

Upon arrival at each study location, two background area samples were collected just outside the containment structure. These samples were collected for a period of time ranging from 3.5 hours to 5 hours before any of the DTC devices were operated. The purpose of these samples was to provide a measure of background conditions inside the lamp recycling facility.

Personal and area air samples were collected within the containment structure for the entire time it took the operator to fill one to two 55-gallon drums with crushed lamps for each DTC device (approximately 60 to 110 minutes). Personal air samples were collected by placing the air pumps on the operator's belt and securing the collection media on the operator's shoulder in order to collect air from within his/her breathing zone (*refer to Photograph 3. 3*, *Photograph 3. 4*, *and Photograph 3. 5*). The personal air samples were collected in order to measure the operator's exposure to airborne mercury during different operational activities.

Groups of personal air samples were also collected separately during the filter change and drum change processes for each device, as appropriate. Once the filter change or drum change, which took between two and 10 minutes, had been completed, the operator remained inside the containment structure to allow at least 12 full minutes for sample collection to ensure that the amount of mercury captured in the sample tube was greater than the detection limit (0.01 µg/sample).

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[11] *When a sample is referred to as a "Filter Change Sample," it is a personal air sample taken when the DTC device filter was changed at a time other than during a drum change. This sample is specific to the Manufacturer C and Manufacturer D devices. The Manufacturer A device did not require a filter change during the Study. For the Manufacturer B device, the filter was changed at the same time that the drum was changed, so a separate "Filter Change Sample" was not needed. Personal air samples that were taken when the drum was changed are referred to in this report as "Drum Change Samples."*

Photograph 3. 3: Feeding Bulbs into the Manufacturer A Device

Photograph 3. 4: Feeding Bulbs into the Manufacturer B Device

Photograph 3. 5: Feeding Bulbs into the Manufacturer C Device

During portions of the Study, short-term "ceiling" air samples were taken. The ceiling samples were another set of personal air samples, which were collected to attempt to quantify airborne mercury concentrations at the estimated time of

maximum exposure. Readings taken on the Jerome analyzer indicated that maximum exposure conditions most probably occurred during drum changes. Thus, the ceiling samples were collected during one of the drum changes for each device during PVS-Phase II, EFT #2, and EFT #3. Two samples were collected on the operator's shoulder, in sequence; each ceiling sample was collected for four minutes.

Area samples were collected by placing the air pumps and collection media on elevated surfaces in specified areas (*refer to Photograph 3. 1 and Photograph 3. 7*) to measure the general airborne mercury concentration inside the containment structure. During operation of each device, four area samples were collected in each phase of the PVS, and two area samples were collected in all three parts of the EFTS.

In addition to the area samples collected during the operation of each device, overnight samples were collected as part of the EFTS. The purpose of the overnight samples was to measure the release of mercury when the DTC devices were not operating, thus simulating a realistic field scenario. At the end of each day of the EFTS, each DTC device remained inside the containment structure, attached to a drum containing crushed lamps, once crushing activities for the second drum were completed. Two to three area air samples were then collected for six to 18 hours. At EPSI Phoenix, the overnight samples were collected inside the containment structure, near the device exhaust and device feed tube. During EFT #2 and EFT #3, overnight samples were collected outside of the containment structure in addition to the samples collected at the device exhaust and device feed tube inside the containment structure.

At the end of each day of sampling, the sampling pumps were removed from the containment structure and taken to the calibration room to be post calibrated. The sampling trains were taken apart, and the mixed cellulose filters and Hydrar tubes were immediately capped on both ends. All information regarding sample duration and air pump calibrations were recorded on air sampling data forms at that time (*refer to Appendix B*). The capped samples were then placed in labeled re-sealable plastic bags and kept at the facility.

At the completion of the sampling event at each study location, all analytical air samples were collected, packaged, and shipped via Federal Express to Data Chem Laboratories, Inc. (Data Chem), along with the completed chain-of-custody forms. Data Chem is an American Industrial Hygiene Association accredited laboratory located in Salt Lake City, Utah. Air sampling media were supplied by Data Chem.

The following sections provide details on the sampling protocol used for each stage of the DTC Device Study.

3.1.1 Performance Validation Study

Phase I of the PVS was conducted February 24-28, 2003, at the AERC facility in Ashland, Virginia (AERC Ashland), and it included the DTC devices from all four manufacturers. AERC Ashland was also the site location for Phase II of the PVS. This phase was conducted June 9-13, 2003 and included 3 DTC devices

(Manufacturer A, Manufacturer B, and Manufacturer C). (*Refer to Section 3.5.3 for a discussion of the exclusion of the Manufacturer D device.*)

The PVS was conducted to examine the effectiveness of each device in capturing and retaining mercury vapors and any potential change in effectiveness over time. The Study compared the results among the different devices when new, and after a pre-determined period of operation during which numerous lamps were processed through each device. The analytical air samples collected for PVS-Phase I were also used in the Mass Balance Study to calculate the release of mercury from the devices.

Table 3. 1 lists the air samples collected for the PVS, and the sampling locations are shown in Figure 3. 1.

Table 3. 1: Analytical Air Samples Collected during the Performance Validation Study

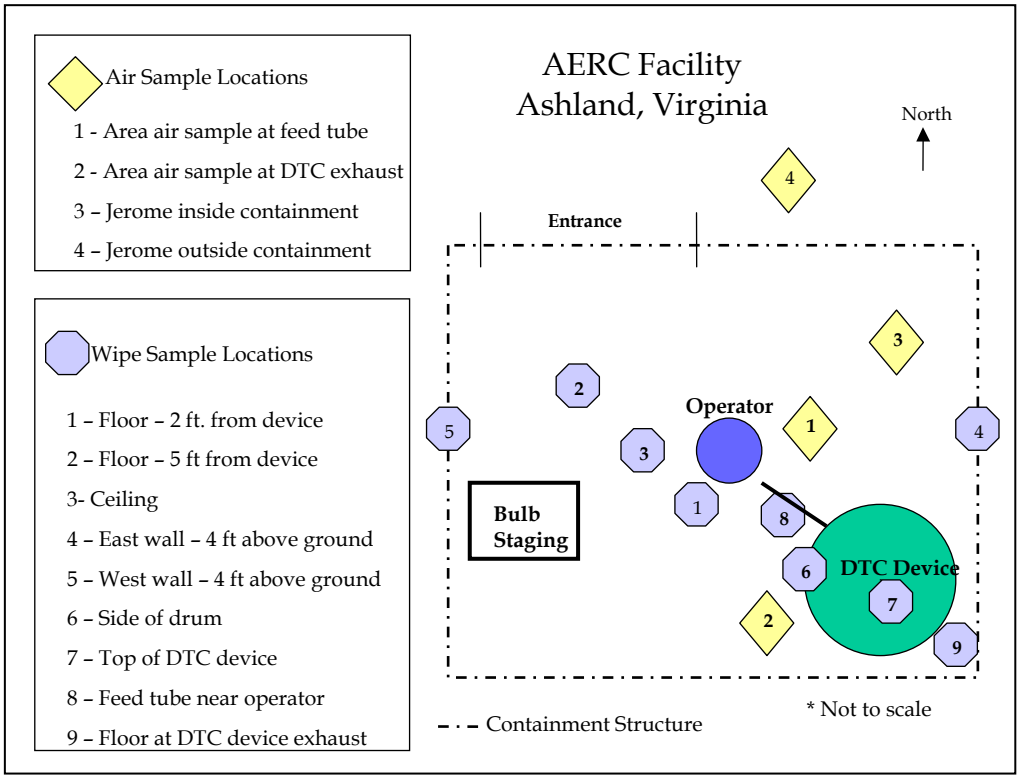
	Type of Sample	# of Samples	Approximate Duration (min)
Personal Samples	1 on each shoulder – filling the drum	2	50 – 115
	1 on left shoulder – during drum/filter change	1-2[a, b]	6 – 18
Area Samples	Near device exhaust	2	50 – 115
	Near device feed tube	2	50 – 115

[a] Manufacturer A: 1 Drum Change Sample
Manufacturer B: 1 Drum Change Sample
Manufacturer C: 1 Filter Change Sample, 1 Drum Change Sample
Manufacturer D: 1 Filter Change Sample, 1 Drum Change Sample (only Phase I).
[b] The filter change samples for the Manufacturer C device were taken when the drum was half full (~350 bulbs).

Manufacturer C and Manufacturer D devices required one filter change per drum in addition to the filter changes performed during drum changes. The personal sample on the shoulder of the operator during the filter change for the Manufacturer C device was performed when the drum was half full of fluorescent light bulbs, equivalent to approximately 350 crushed bulbs. This was true for all filter change samples collected for the Manufacturer C device throughout the DTC Device Study.

Due to exposure levels significantly above the OSHA PEL, only 276 bulbs were crushed in the Manufacturer D unit during Phase I of the PVS. The Manufacturer D device was removed from the study after EFT #1 (refer to Section 3.5.3), so the samples listed for this device in Table 3. 1 were only collected during PVS – Phase I.

Figure 3. 1: Sampling Locations for the Performance Validation Study and Extended Field Test #3



3.1.2 Extended Field Test #1

The EFTS was conducted to examine the ongoing performance of each device during extended use and over a range of environmental conditions. EFT #1 was conducted at the EPSI facility in Phoenix, Arizona (EPSI Phoenix), March 24-28, 2003, and it included four DTC devices (Manufacturer A, Manufacturer B, Manufacturer C, and Manufacturer D). Air samples collected during EFT #1 are described in Table 3. 2, and Figure 3. 2 shows the sample collection areas.

Table 3. 2: Air Samples Collected during Extended Field Test #1

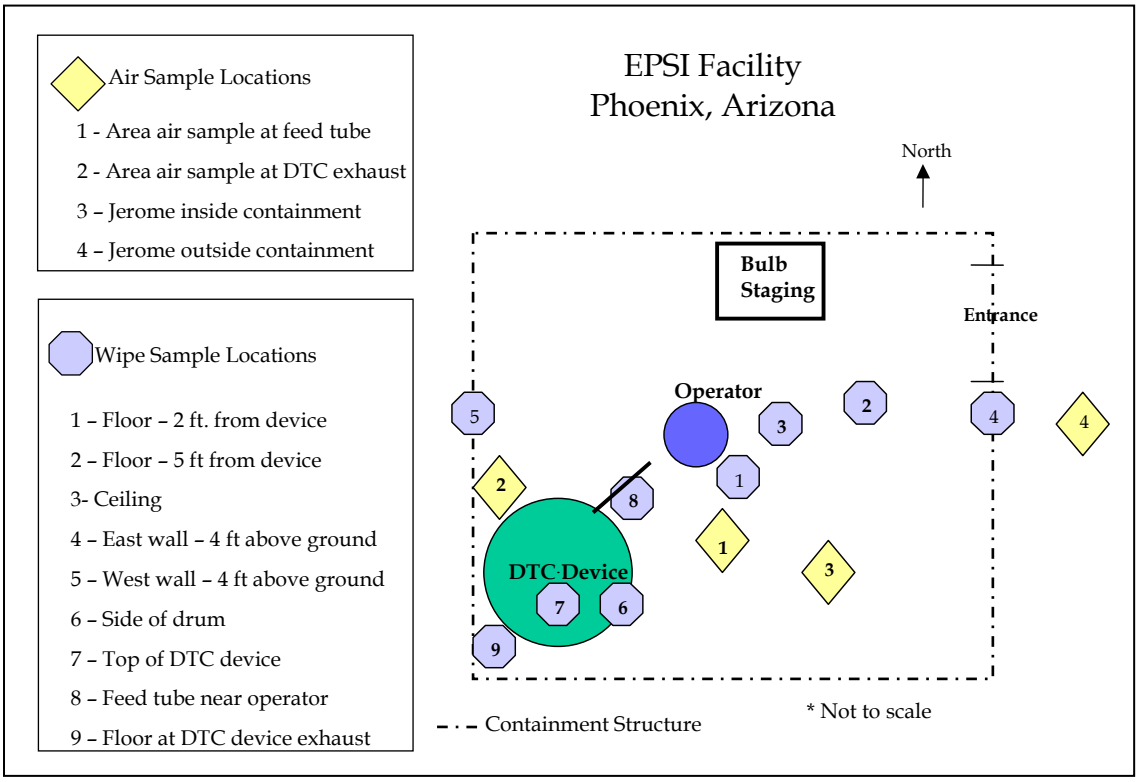
	Type of Sample	# of Samples	Approximate Duration (min)
Personal Samples	1 on each shoulder – filling the drum	2	125 – 200
	1 on left shoulder – during drum/filter change	1-3[a, b]	12 – 36
Area Samples	Near device exhaust	1	125 – 200
	Near device feed tube	1	125 – 200
Overnight Samples	Near device exhaust	1	440 – 780
	Near device feed tube	1	420 – 780

[a] Manufacturer A: 1 Drum Change Sample
Manufacturer B: 2 Drum Change Samples
Manufacturer C: 2 Filter Change Samples, 1 Drum Change Sample
Manufacturer D: NONE
[b] The filter change samples for the Manufacturer C device were taken when the drum was half full (~350 bulbs).

The Manufacturer D device was removed from the Study during Extended Field Test (EFT) #1 because Jerome measurements of mercury vapor concentrations in the

containment structure reached 0.59 mg/m^3, nearly six times the OSHA PEL. Further information can be found in Section 3.5.3.

Figure 3. 2: Sampling Locations for Extended Field Test #1



3.1.3 Extended Field Test #2

Air samples were collected during EFT #2 at the AERC facility in Melbourne, Florida (AERC Melbourne), April 28 – May 3, 2003, for three DTC devices (Manufacturer A, Manufacturer B, and Manufacturer C). Short-term ceiling air samples were introduced into the Study during this round of testing. As described above, ceiling samples were air samples collected over a short duration in time in an attempt to quantify airborne concentrations at the estimated time of maximum exposure.

Readings taken on the Jerome analyzer indicated that maximum exposure conditions most probably occurred during drum changes. Drum change sample results from EFT #1 showed that the ambient concentration of mercury is sufficiently high during drum changes such that the samples did not need to be collected for 12 minutes in order to exceed detection limits. Thus, two short-term, personal air samples were collected in sequence during one of the drum changes for each device. The sampling time was four minutes per sample, for a total duration of eight minutes.

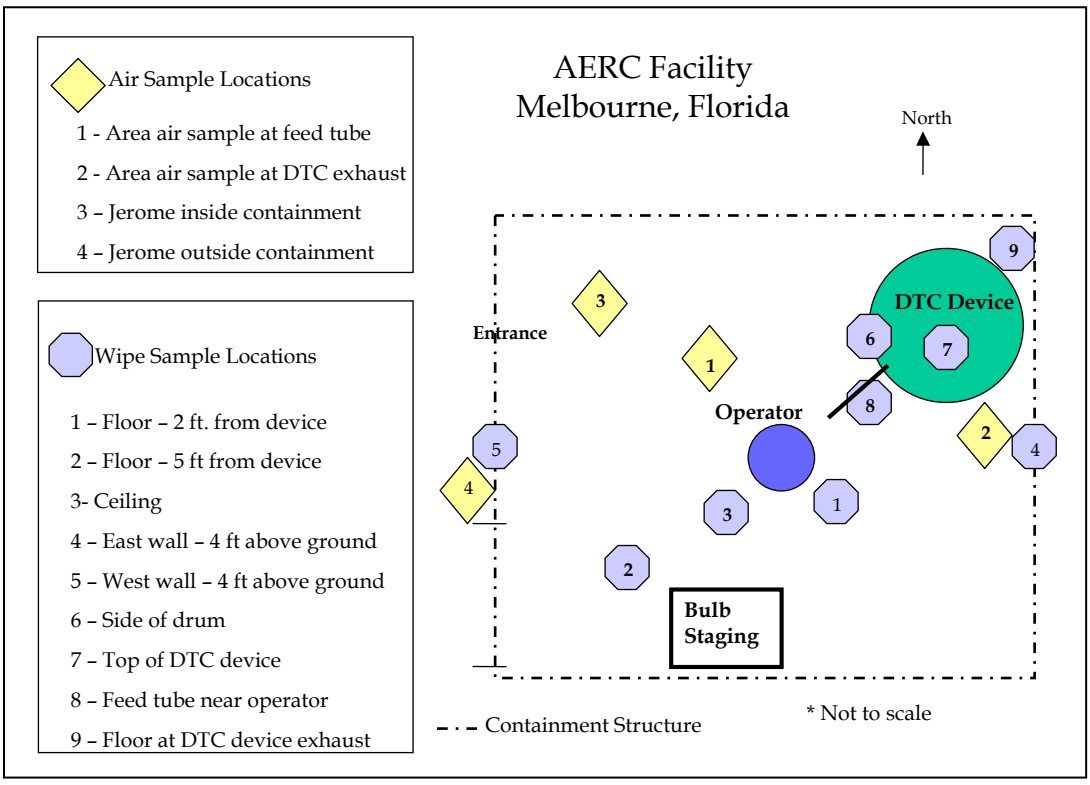
Table 3. 3 lists the analytical air samples collected in EFT #2. Sampling locations at the Florida facility are shown in Figure 3. 3.

Table 3. 3: Air Samples Collected during Extended Field Test #2 and #3

	Type of Sample	# of Samples	Approximate Duration (min)
Personal Samples	1 on left shoulder – filling both drums, filter changes, drum changes	1	100 – 160
	1 on each shoulder – filling 1st drum	2	60 – 80
	1 on each shoulder – filling 2nd drum	2	40 – 70
	1 on left shoulder – during drum/filter change	2-4[a, b]	12 – 20
Ceiling Samples	1 on shoulder – samples taken in sequence during drum change	2	4
Area Samples	Near device exhaust	1	100 – 160
	Near device feed tube	1	100 – 160
Overnight Samples	Near device exhaust	1	720 – 1080
	Near device feed tube	1	720 – 1080

[a] Manufacturer A: 2 Drum Change Samples
Manufacturer B: 2 Drum Change Samples
Manufacturer C: 2 Filter Change Samples, 2 Drum Change Samples
[b] The filter change samples for the Manufacturer C device were taken when the drum was half full (~350 bulbs).

Figure 3. 3: Sampling Locations for Extended Field Test #2



3.1.3.1 Box Test

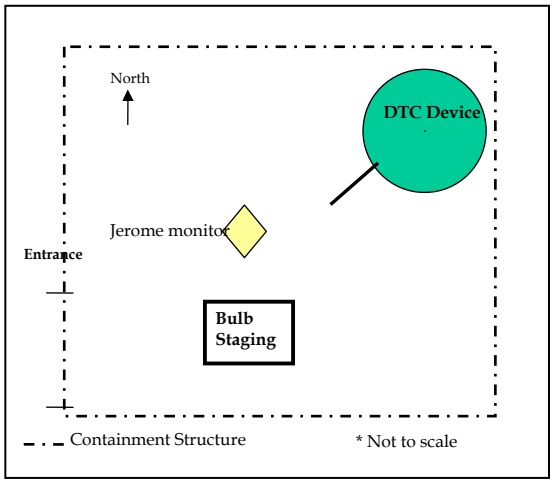
On the first day at AERC Melbourne (EFT #2), the Manufacturer B device was operated and mercury levels were measured. The Jerome analyzer measured airborne mercury levels that exceeded the OSHA PEL: (1) while operating the device to fill the first drum, (2) during the down time taken by the operator after filling and changing out the first drum, and (3) for the first 20 minutes of device operation, while filling the second drum. Because the Manufacturer B Device had previously shown better performance and because mercury levels in the

containment structure had declined during other non-operational periods (i.e., periods during the operator break between drums when devices were not operated), the field team decided to try to evaluate the cause of the high mercury readings.

During Phase I of the PVS and EFT #1 and the beginning of EFT #2, multiple cardboard boxes of fluorescent lamps were brought into the containment structure and kept inside to ensure that the operator had an adequate supply of readily accessible lamps. The field team suspected that the mercury released from the broken lamps in the boxes was contributing to elevated levels inside the containment structure. Based on this concern, testing procedures were revised so that only one box of lamps was kept inside the containment structure.

On April 30 (EFT #2), a test was performed to determine whether the boxes containing broken lamps were contributing to elevated mercury concentrations inside the containment structure (Box Test). Five boxes containing some broken lamps were brought into the containment structure. A Jerome analyzer was also placed inside the containment structure to record the airborne concentrations of mercury. Figure 3. 4 shows the layout of the containment area and sampling locations for the mercury emission test from broken boxed lamps.

Figure 3. 4: Box Test Configuration, AERC Melbourne



At the end of the week, the decision was made to repeat a portion of the Manufacturer B device testing, following the new procedure of bringing only one box at a time into the containment structure. Due to time constraints, the repeat test included only one drum, not two drums as in the first test at this location.

3.1.4 Extended Field Test #3

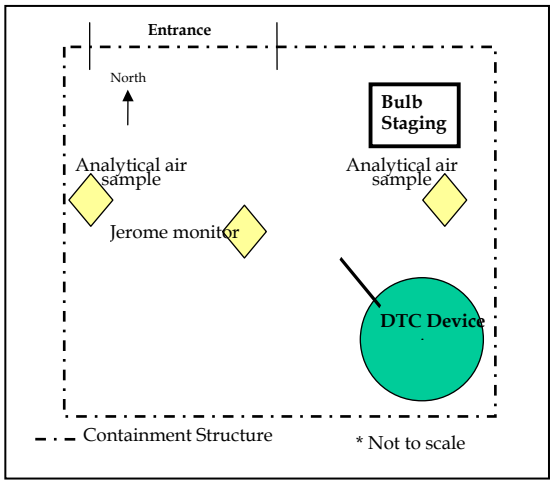
The third EFT was conducted at AERC Ashland, during the same time period as Phase II of the PVS, June 9-13, 2003. Three DTC devices (Manufacturer A, Manufacturer B, and Manufacturer C) were included in this portion of the Study. At the conclusion of EFT #3 for each DTC device, the containment structure polyethylene was replaced with new polyethylene, and Phase II of the PVS for that device began. Table 3. 3 lists the samples collected for EFT #3. Because this test was

conducted at AERC Ashland, the sampling locations are the same for PVS Phase I, PVS Phase II, and EFT #3 (*refer to Figure 3. 1*).

3.1.4.1 Box Test

A Box Test was also conducted at AERC Ashland in a similar manner to the test at AERC Melbourne, with the addition of analytical air samples collected on the east and west sides of the containment structure. Refer to Figure 3. 5 for the containment area layout and sampling areas for the Ashland Box Test. The test was performed at the conclusion of EFT #3 and before the beginning of PVS – Phase II for each device (Manufacturer A, Manufacturer B, and Manufacturer C devices).

Figure 3. 5: Box Test Configuration, AERC Ashland



3.1.4.2 U-Tube Test

The majority of fluorescent lamps processed in the Study were four-foot straight tubes. Although the DTC devices included in the Study were designed to process straight lamps, only two devices (Manufacturer B and Manufacturer C) have attachments that enable them to process "U" shaped fluorescent lamps (U-tubes), as well. At the end of EFT #3 at AERC Ashland, a test was conducted to evaluate airborne mercury levels from the two devices while processing U-tubes. The intent was for both the Manufacturer B and Manufacturer C devices to process enough U-tubes to fill a 55-gallon drum. However, the facility was only able to collect a limited number of U-tubes for the U-tube study. Therefore, the total quantity of U-tubes was divided between the two devices. The Manufacturer B device processed a total of 85 U-tubes, and the Manufacturer C device processed a total of 89 U-tubes.

Table 3. 4 lists the analytical air samples collected during the processing of the U-tubes. Air sample locations correspond to the locations shown in Figure 3. 1; however, there were no wipe samples collected for the U-tube evaluation. Photograph 3. 6 shows the crushing of U-Shaped.

Table 3. 4: Air Samples Collected during U-tube Evaluation

	Type of Sample	# of Samples	Approx. Duration (min)	Air Flow Rate (cc/min)
Personal Samples	1 on each shoulder – filling the drum	2	12 – 14	150
Area Samples	Near device exhaust	1	12 – 14	150
	Near device feed tube	1	12 – 14	150

Photograph 3. 6: Crushing of U-Tubes – Manufacturer C Device

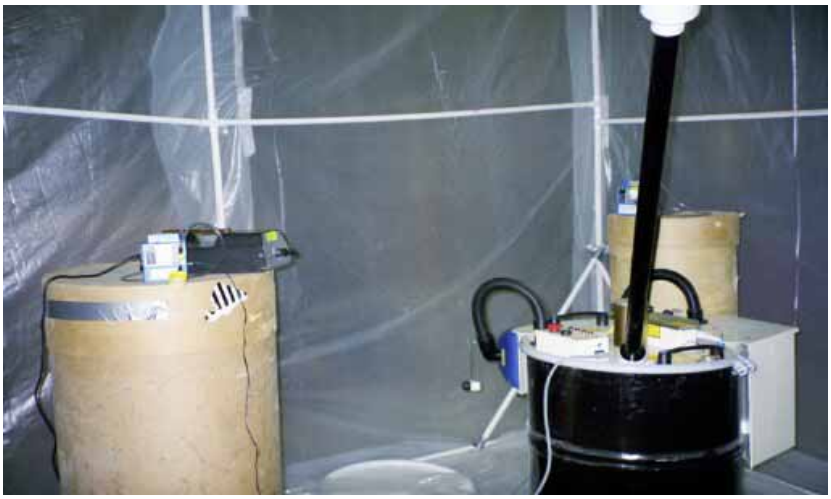
3.2 Jerome Mercury Vapor Analyzer Samples

In addition to measuring mercury concentrations in the air using sampling pumps, two factory-calibrated Jerome Mercury Vapor Analyzers (Model 431-X, Arizona Instrument, LLC) were used to measure real-time mercury concentrations in the ambient air. As shown in Figure 3. 1, Figure 3. 2, and Figure 3. 3, one stationary Jerome analyzer (Jerome #1) remained inside the containment structure (*refer to Photograph 3. 1 and Photograph 3. 7*), while another Jerome analyzer (Jerome #2) was placed outside of the containment structure and brought inside at various times.

Both analyzers were used to identify fluctuations in concentrations while the DTC devices were operated. The Jerome analyzer accurately measures mercury within $\pm$ 5% in the sensitivity range of 0.003 to 0.999 mg/m^3 mercury. Both analyzers were equipped with data loggers, to measure and record the mercury concentrations throughout the day. However, due to problems with the data loggers, the analyzers had to be checked manually and the concentrations recorded in field notebooks.

Jerome #2 was specifically utilized to identify emissions at the carbon filter exhaust, leaks around the seals, emissions/releases at the feed tube, varying concentrations within the containment structure, and background conditions outside the containment structure. This information assisted the operators in determining when personal protective equipment (PPE) was necessary. The mercury vapor analyzer alarms were set to activate at 0.05 mg/m^3, to alert the operator of the mercury concentration before the OSHA PEL (0.1 mg/m^3) was approached. The project health and safety plan specified that respiratory protection be used inside the containment structure if mercury levels reached or exceeded 0.05 mg/m^3. It was

common for mercury concentrations to exceed 0.05 mg/m^3 during routine operation; therefore, respiratory protection was employed throughout most of the Study.



Photograph 3. 7: Placement of Air Sampling Pump & Jerome Analyzer in Relation to DTC Device

3.3 Bulk Samples

The Mass Balance Study was intended to account for the fate of the mercury involved in the operation of DTC devices by estimating the total mass of mercury put into the DTC device via crushed lamps and comparing that quantity to the mass of mercury retained by the device plus the mass of mercury released. Samples of unbroken, spent lamps were collected to quantify the average amount of mercury in different types of fluorescent lamps and estimate the total amount of mercury processed by each device. Pollution control media samples and samples of crushed lamps were used in the Mass Balance Study to estimate the amount of mercury retained within the drum and the device assembly for each device.

3.3.1 Unbroken Spent Lamps

During Phase I of the Performance Validation Study (PVS), several unbroken, spent fluorescent lamps were submitted to Data Chem for mercury analysis. Alto® lamps, manufactured by Philips Lighting, were collected and used for this portion of the Study. Specifically, three Alto® T8 lamps, three T12 34-watt lamps, and two Alto® T12 40-watt lamps were obtained from AERC Ashland and analyzed.

Data Chem used a low-temperature drill and acid extraction method to collect the mercury in the lamps, and performed the analysis in accordance with EPA Method 7470. The method used by Data Chem is a non-standardized method based on discussions between Data Chem and Philips Lighting. Philips Lighting shared information with Data Chem on experiments performed to extract mercury from an operating lamp. Data Chem modified the mercury extraction method to extract mercury from a spent lamp rather than an operational lamp (*refer to Appendix E for a description of Data Chem's extraction method*).

Briefly, the method involved packing the lamps in dry ice for approximately one hour, to chill them and condense the mercury vapors inside. A small hole was then drilled into the end cap, and concentrated nitric acid was introduced into the lamps. The hole was filled with a wax plug and the lamps were agitated for approximately 15 minutes, to allow the mercury to react with the acid. The acid was removed from the lamp and analyzed using EPA Method 7470. The results were used to confirm the amount of mercury reported by Philips Lighting and to calculate the quantities of mercury for the Mass Balance Study.

3.3.2 Pollution Control Media

During Phase I of the PVS, bulk samples of various pollution control media were collected from each DTC device after the operator had filled one drum with lamps. Bulk samples were collected from the filter media prior to removing the device from the containment structure (*refer to Appendix H for detailed procedures for the collection of samples from the pollution control media*).

The bulk samples collected from each of the DTC devices included:

- Three samples of particulates from the particulate pre-filters from the Manufacturer B device, Manufacturer C device, and Manufacturer D device (the Manufacturer A device is not equipped with a particulate pre-filter).

- Three samples of particulates from the HEPA filters from all four devices.

- Three samples of particulates from the carbon filters from all four devices.

Clean filter media were submitted by the manufacturers to Data Chem for quality control (QC) samples. These clean materials were used for blank samples and spike samples so that comparisons could be made to the samples of the used filter media. The samples were analyzed in accordance with EPA Method 7470 and EPA Method 7471A, modified slightly by Data Chem to accommodate materials other than soil or sediment, as outlined in Appendix E.

Before the start of lamp crushing operations, the filters (pre-filter, HEPA filter, and carbon filter) and empty drums were weighed for each device. After the drum was completely full, the drum and filters were re-weighed to determine the amount (by weight) of crushed lamps in the drum or particulate on the filters.

3.3.3 Crushed Lamps

After the samples from the pollution control media were collected, the DTC device was removed from the top of the drum. Three samples of crushed lamps were collected for each device to determine the amount of mercury in a drum of crushed lamps for the Mass Balance Study. Approximately 275 to 300 cubic centimeters (cm^3) of crushed lamps was collected from each drum using dedicated, disposable plastic spoons that had been decontaminated (prior to use) with HgX® in clean water and

allowed to air-dry.[12] The samples were collected from as deep within the drum as possible to minimize the potential for low-biased results due to vaporization or fugitive particulate emissions of mercury. However, due to the density of the crushed lamps, the sampling depth was limited to approximately eight inches. The samples were sealed in sample containers provided by Data Chem Laboratories.

After collection, all the bulk samples (i.e., unbroken spent lamps, pollution control media, and crushed lamps) were packaged and shipped via Federal Express to Data Chem for analysis along with completed chain-of-custody forms that were signed by the personnel who collected the samples.

3.4 Wipe Samples

Surface wipe samples were collected inside the containment structure on numerous surfaces both before and after lamp crushing, as part of the Mass Balance Study. The wipe samples were collected and analyzed in accordance with N9103 for wipe samples (*refer to Appendix E*). Under this procedure, a 100 square centimeter (cm^2) area was wiped using a "Wash N' Dri" towelette (the liquid component of the wipe is 5 to 10 percent ethanol and 80 to 90 percent water), which was placed into a glass vial. Wipe sample supplies were provided by Data Chem (*refer to Photograph 3. 8*).

Photograph 3. 8: Wipe Sample Media

Wipe samples were collected prior to the start of each DTC device operation and again at the conclusion of the DTC device operation. The pre-test and post-test samples were collected in the same general area; however, the post-test wipe samples may not have been collected in the exact location of the pre-test wipe sample *(refer to Figure 3. 1, Figure 3. 2, and Figure 3. 3 for sample collection areas)*.

For the testing conducted at AERC Ashland during PVS – Phase I, a set of two pre-test wipe samples and a set of two post-test wipe samples were collected at each of the nine locations shown in Figure 3. 1. The purpose of this activity was to assess the reproducibility of the results. However, although the testing at AERC Ashland indicated, widely divergent values (i.e., orders of magnitude differences), most likely

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[12] *HgX® is a sulfiding and chelating agent that contains sodium thiosulfate and EDTA.*

attributable to the high background level of airborne and surficial mercury contamination, it was not possible to modify the study design to increase the number of replicates of wipe samples at the other locations.

After sampling was complete at each of the study locations, the wipe samples were collected for shipment to Data Chem. Samples were placed in an oversized sturdy box with packing material to fill voids and protect the samples during shipping. The chain-of-custody forms were then signed by the sampling personnel and placed in the box with the samples. Samples were shipped via Federal Express to the laboratory.

3.5 Test Protocol Deviations and Modifications

Due to circumstances encountered in the field, it was not always possible to follow the initial testing protocol. The following sections describe deviations in device operation and modifications to testing procedures, which were mainly associated with difficulties encountered while processing lamps.

3.5.1 Manufacturer B Device

For EFT #1, the vendor provided the operator with a reducer plate to install in the Manufacturer B device at the carbon filter exhaust. The reducer apparently was designed to throttle airflow through the unit, and was installed at EPSI Phoenix per the vendor's instructions. Increased emissions occurred while the DTC device was being tested, apparently as a consequence of the newly installed reducer. After processing the first full drum of crushed lamps, a representative from Manufacturer B was contacted and a decision was made to remove the reducer plate and then to continue the crushing operations for the second drum without the plate.

3.5.2 Manufacturer C Device

For EFT #1 at EPSI Phoenix, the Manufacturer C device experienced some operational difficulties that delayed the start of testing and may have had an effect on the results measured during the operation. After the first lamp was inserted into the feed tube, the motor on the machine stopped. After troubleshooting the problem, the manufacturer found that the machine would start if the start button were depressed for approximately 10 seconds. Depressing the start button for 10 seconds enabled a safety lock operating off a pressure sensor to be disengaged. The operator proceeded to crush lamps, and changed a filter after 350 lamps were crushed. The drum and filter were changed once the first drum was filled with 750 lamps. During crushing operations for the first drum, the operator noted that the feed tube jammed about every 20 bulbs and had to be cleared by sliding a rod down the feed tube.

Due to on-going operational problems and elevated mercury levels, testing of this device was concluded after only 336 bulbs had been crushed in the second drum. The device was returned to the manufacturer to evaluate the cause of the operational difficulties. The manufacture installed a new control panel for the device and then

shipped the machine to Melbourne, Florida for EFT #2. The device was able to process the required number of lamps during EFT #2, EFT #3, and the PVS.

3.5.3 Manufacturer D Device

During PVS – Phase I, elevated levels of mercury vapor were detected during testing of the Manufacturer D device (*refer to Section 4.4.1.2*). These levels required the temporary suspension of the test to allow the operator to don respiratory protection (after crushing 25-30 fluorescent lamps). The test was permanently suspended (after crushing 276 lamps) at this site because mercury concentrations consistently exceeded the OSHA PEL and continued to increase. The readings on the Jerome analyzer peaked at 0.89 mg/m^3, nearly 9 times the OSHA PEL.

The Manufacturer D device was shipped back to the Manufacturer D facility at the manufacturer's request to evaluate the cause(s) of the elevated ambient mercury measurements. EPA requested that the manufacturer prepare a written report detailing the problem(s) and the cause(s); the report was also required to confirm the adequacy of the repairs, including an analysis for mercury vapor by a qualified industrial hygienist.

The device arrived at EPSI Phoenix (EFT #1) for the next round of testing visibly damaged and modified to the extent that it looked like a different device than the device used for Phase I of the PVS. The overall study design required each DTC device vendor to provide one unit that would be used throughout the entire test. Changing the device design violated the study design. There was also a clearly visible crack in the vacuum assembly, preventing adequate negative pressure when the device was turned on, and some of the carbon from the pollution control media spilled out of device during assembly. Even though only 16 lamps were crushed during testing, the ambient mercury concentration inside the containment structure, measured by the Jerome analyzer, reached 0.406 mg/m^3 mercury, more than four times the PEL.

None of the analytical air samples taken for this device were below the ACGIH TLV. Eight analytical air samples were collected during PVS – Phase I, and only one was below the PEL. Only two of the four samples collected during EFT #1 (when only 16 lamps were crushed) were below the PEL. It was determined that the use of the Manufacturer D device posed a health risk to study personnel, particularly the operator and assistants. After serious consideration, the unit was eliminated from further testing because of the unauthorized modifications and because of continued elevated mercury levels. Further information can be found in Appendix I.

4. RESULTS AND DATA EVALUATION

The overall objective of the DTC Device Study was to gain insights into the abilities of four different DTC devices to capture and contain mercury, while processing fluorescent lamps. A variety of air and other samples were collected for distinct tests that comprise the DTC Study.[13] This chapter presents the data collected for the Performance Validation Study (PVS) and the Extended Field Test Study (EFTS) and evaluates those results against study objectives. The next chapter (Chapter 5) presents and evaluates the data collected for the Mass Balance Study. The objectives for the different studies discussed in this chapter are listed below.

- The PVS was conducted to examine the effectiveness of each device in capturing and retaining mercury vapors and to identify any potential change in effectiveness over time. The study compared the results among the different devices when new and after a pre-determined period of operation during which numerous lamps were processed through each device (Section 4.4).

- The EFTS was conducted to examine the ongoing performance of each device during extended use and over a range of environmental conditions (Section 4.5).

- The Box Tests, conducted as part of the EFTS, were performed as an addendum to the EFTS to determine if the presence of broken lamps inside the containment structure confounded the study results (Section 4.6).

- The Overnight Tests were performed as part of the EFTS to evaluate releases of mercury vapor from DTC devices attached to partially filled drums during non-operational periods (Section 4.7).

- The U-tube Test, conducted as part of the EFTS, examined the performance of two of the devices when processing U-shaped fluorescent lamps (Section 4.8).

4.1 Exposure Evaluation Criteria

The results from the analytical air samples and the Jerome analyzers were compared to published mercury exposure limits to assess the performance of the devices in effectively capturing mercury vapors, while processing fluorescent lamps.

<u>OSHA PEL</u>: The federal Occupational Safety and Health Administration (OSHA) has established a maximum work-place regulatory permissible exposure limit (PEL) for inorganic mercury, which is codified in 29 Code of Federal Regulations (CFR) 1910.1000, Table Z-2. The current mercury exposure limit for workers is 0.1 mg/m^3 (ceiling). This regulatory exposure limit is established as a "ceiling" value in the

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[13] *It is important to note that, out of the 199 analytical air samples collected, only eight mercury aerosol (MCE filter) samples had values above the detection limit, and all blank MCE filter samples were below the detection limit. All of the mercury vapor (Hydrar tube) samples contained levels of mercury above the detection limit. Because the amount of mercury aerosol was not high enough to measure, the air results discussed in this chapter only address the Hydrar tube samples. The results for the MCE filters can be found in Appendix A, Table 1. Future research may be necessary to determine why aerosols were generally not detected (refer to Section 7.4).*

CFR, meaning that exposure to this value is not to be exceeded during any part of the work day, as opposed to a time weighted average (TWA) that calculates average exposure over the entire work shift. [14] However, in a memo dated September 1996, it states that OSHA currently implements the mercury PEL as an eight-hour TWA rather than as a ceiling value.[15]

ACGIH TLV: The other exposure limit that is referenced in this report regarding DTC device performance is a published work-place exposure limit, the threshold limit value (TLV) established by the American Conference of Governmental Industrial Hygienists (ACGIH), which is a professional organization for individuals in the industrial hygiene and occupational health and safety industry. The ACGIH TLV is 0.025 mg/m^3 and is a TWA (eight hours per day, 40 hours per week).[16]

EPA has established an exposure limit (a reference concentration, or RfC) of 3.0x10^{-4} mg/m^3 for the general public for chronic exposure to elemental mercury.[17]

The data from analytical air samples taken in this Study represent average values for the time periods during which the samples were taken; sampling time was generally between one and three hours for the samples taken during device operation (*refer to Appendix A, Table 1 for sample durations*). Sample results that are greater than the TLV value should not necessarily be interpreted to indicate that use of one of the DTC devices included in the Study would result in operator exposure above the TLV because the device may not be used for eight hours per day, 40 hours per week. The analytical air sample results were not normalized to an eight hour workday because DTC device use patterns may vary significantly (e.g., from a few minutes to eight or more hours per day). More information about the actual use patterns of DTC devices and the mercury exposures experienced by workers during non-operational periods would be necessary in order to calculate an eight hour TWA accurately for any specific pattern of use.

4.2 Background Air Samples

Because the Study was being conducted at commercial lamp recycling facilities, which were expected to have ambient mercury concentrations above those in outdoor air, three types of background samples were collected in order to quantify the mercury present at each site before, during, and after device operation.

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14 *Refer to 29 CFR 1910.1000(b).*

15 *The PEL for mercury was promulgated as a ceiling value in 1971 (36 FR 10505, May 29, 1971). A memorandum to OSHA compliance personnel was issued on September 3, 1996, that directs compliance officers to issue citations only when an overexposure exceeds 0.1 mg/m^3 as an 8-hour TWA.*

16 *ACGIH also has a "skin" notation for elemental mercury, indicating that dermal absorption is another possible exposure route. Refer to ACGIH (1994). 1994-1995 Threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.*

17 *The inhalation Reference Concentration (RfC) is intended to identify a maximum safe level for chronic exposure for the general population and is analogous to the oral RfD. The inhalation RfC considers both toxic effects for the respiratory system and toxic effects peripheral to the respiratory system (extrarespiratory effects). In general, the RfC is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily inhalation exposure of the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. The mercury RfC is based on a human lowest observed effect level (LOEL) of 0.025 mg/m^3. See Integrated Risk Information System (IRIS) website (www.epa.gov/iris/index.html) for further discussion.*

- On the first day at each site, before performing any crushing activities, two analytical air samples were collected in the vicinity of the study area, to measure ambient mercury concentrations in the lamp recycling facility (*refer to Table 4. 1*).

- During testing at AERC Melbourne and the second round of testing at AERC Ashland, one analytical air sample was taken overnight outside the containment structure at the end of each day of testing (*refer to Table 4. 1 for overnight background results and refer to Section 4.7 for information on overnight tests*).

- Jerome readings from a Jerome analyzer positioned outside the containment structure were manually recorded during PVS – Phase II and during the EFTS as time allowed (*refer to Table 4. 2*).

Table 4. 1: Background Mercury Results – Analytical Air Samples

Studies	Date	Location	Mercury Concentration (mg/m^3)	Mean (mg/m^3)
Performance Validation I	2/25/2003	Middle of E. bay	0.0039	0.0043
	2/25/2003	E. bay by center bay door	0.0047	
Extended Field Test #1	3/24/2003	N. of containment in bay	0.014	0.010
	3/24/2003	E. of containment in bay	0.0059	
Extended Field Test #2	4/29/2003	24 ft. E. of dock door	0.016	0.0164
	4/29/2003	18 ft. N. of dock door	0.012	
	4/29/2003	Outside containment-night	0.021	
	4/30/2003	Outside containment-night	0.016	
	5/01/2003	Outside containment-night	0.017	
Extended Field Test #3 & Performance Validation II	6/09/2003	Middle of E. bay	0.013	0.0166
	6/09/2003	E. bay by center bay door	0.0086	
	6/10/2003	Outside containment-night	0.017	
	6/11/2003	Outside containment-night	0.00052	
	6/12/2003	Outside containment-night	0.044	

Table 4. 2: Background Mercury Results – Jerome Analyzer Measurements

Studies	Date	Location	Mercury Concentration (mg/m^3)	Mean (mg/m^3)
Performance Validation I		No data	No data	
Extended Field Test #1	3/24/2003	Inside containment before crushing	0.020	0.029
	3/24/2003	Inside manager's desk	0.023	
	3/24/2003	Inside manager's desk	0.022	
	3/24/2003	Inside manager's desk	0.023	
	3/24/2003	Minimum outside containment during crushing	0.030	
	3/24/2003	Maximum outside containment during crushing	0.050	
	3/25/2003	Outside containment	0.040	

Studies	Date	Location	Mercury Concentration (mg/m³)	Mean (mg/m³)
	3/26/2003	Outside containment	< 0.003	
	3/27/2003	Inside containment before crushing	0.035	
	3/27/2003	Minimum outside containment during crushing	0.035	
	3/27/2003	Maximum outside containment during crushing	0.045	
Extended Field Test #2	4/29/2003	Outside containment	0.007	0.0074
	4/29/2003	Outside containment	< 0.003	
	5/01/2003	Outside containment	0.004	
	5/01/2003	Outside containment	0.017	
Extended Field Test #3 & Performance Validation II	6/10/2003	Outside containment-after EFT #3, before PVS-II	0.008	0.014
	6/10/2003	Inside containment-after EFT #3, before PVS-II	0.009	
	6/10/2003	Inside containment-after EFT #3, before PVS-II	0.012	
	6/11/2003	Outside containment during operation	< 0.003	
	6/11/2003	Outside containment during operation	0.01	
	6/11/2003	Outside containment during operation	< 0.003	
	6/11/2003	Outside containment during operation	0.004	
	6/11/2003	Outside containment during drum change	0.017	
	6/11/2003	Outside containment-after EFT #3, before PVS-II	0.005	
	6/11/2003	Inside containment-after EFT #3, before PVS-II	0.03	
	6/12/2003	Outside containment before starting	0.013	
	6/12/2003	Outside containment before starting	0.014	
	6/12/2003	Inside containment before starting	0.021	
	6/12/2003	Outside containment between drum 1 & 2, during EFT #3	0.014	
	6/12/2003	Minimum outside containment, during PVS-II	0.020	
	6/12/2003	Maximum outside containment, during PVS-II	0.040	

Each facility had measurable concentrations of mercury in the indoor ambient air. According to research by Garetano, et al. outdoor mercury vapor concentrations generally range from $2*10^{-6}$ to $2*10^{-5}$ mg/m^3, with higher concentrations in urban/ industrial areas.[18] None of the analytical air samples were below the detection limit (0.01 µg/sample), and only four of the 31 mercury concentrations taken with the Jerome analyzer were below the instrument detection limit (0.003 mg/m^3).

The samples taken at the end of each day of testing during EFT #2 and EFT #3 were compared to the background samples taken at the two sites before the DTC device was operated to determine if the industrial lamp crushing activities at the lamp recycling facilities created a significant increase in the background concentration of mercury throughout the week. Based on the four samples collected before beginning DTC device operation and six samples collected overnight after DTC device operation (N=10), there was no significant correlation between the measured background concentration of mercury and the day of the week that the air sample was collected. The background mercury concentrations are considered in the results

[18] *Refer to Garetano, Gary; Gochfeld, Michael; and Stern, Alan H. 2006. Comparison of Indoor Mercury Vapor in Common Areas of Residential Buildings with Outdoor Levels in a Community Where Mercury Is Used for Cultural Purposes. Environmental Health Perspectives. 114(1): 59–62.*

discussions in this chapter. The overall effect of the elevated background mercury levels on the Study is discussed in Chapter 6.

4.3 Blank Air Samples

As described in Section 3.1, NIOSH Analytical Method N6009 was used for mercury air sampling. Data Chem included in all laboratory air sample reports the fact that each Hydrar tube was contaminated with 0.035 to 0.045 micrograms (µg) of mercury.

At the beginning of each portion of the Study, three Hydrar sorbent tubes were set aside as trip blanks. These tubes were never opened during the field sampling and were submitted to the laboratory for analysis with the air samples to determine the level of mercury present in the sorbent material when no air sampling had occurred.

Additionally, at the beginning of each day of sampling, two Hydrar tubes were removed and designated as field blanks. The ends of the glass tubes were opened for several seconds to expose the sampling media to the air in the calibration room, and then were capped and submitted to the laboratory for analysis.

All blank air samples were only handled in the pump calibration room, a room at each facility that was separate from the areas where lamps were being crushed, such as a conference room or an office. The tubes used as blanks were never in the lamp processing areas. Table 4. 3 summarizes the trip blank data, and Table 4. 4 summarizes the field blank data. The means and standard deviations (Std Dev) are included with the results.

Table 4. 3: Trip Blank Results

Study	Blank 1 (µg)	Blank 2 (µg)	Blank 3 (µg)	Mean (µg)	Std Dev
Performance Validation I	NA	NA	NA	NA	NA
Extended Field Test #1	0.056	0.060	0.065	0.0603	0.00451
Extended Field Test #2	0.046	0.048	0.049	0.0477	0.00153
Extended Field Test #3 & Performance Validation II	0.040	0.047	0.040	0.0423	0.00404

NA - Not Analyzed

The analytical results for the trip blanks confirmed the presence of mercury in the sorbent material and were generally slightly higher than the laboratory-provided information regarding mercury contamination associated with Hydrar sorbent tubes.

Table 4. 4: Field Blank Results

Study	Date	Blank 1 (µg)	Blank 2 (µg)	Daily Mean (µg)	Site Mean (µg)	Std Dev
Performance Validation I	2/26/2003	0.040	0.041	0.0405	0.0403	0.0014
	2/27/2003	0.041	0.038	0.0395		
	2/28/2003	0.042	0.040	0.041		
Extended Field Test #1	3/24/2003	0.078	0.086	0.082	0.118	0.0807
	3/25/2003	0.075	0.071	0.073		

Study	Date	Blank 1 (µg)	Blank 2 (µg)	Daily Mean (µg)	Site Mean (µg)	Std Dev
	3/26/2003	0.28	0.21	0.245		
	3/27/2003	0.073	0.071	0.072		
Extended Field Test #2	4/29/2003	0.046	0.044	0.045	0.0470	0.0020
	4/30/2003	0.045	0.048	0.0465		
	5/1/2003	0.046	0.049	0.0475		
	5/2/2003	0.049	0.049	0.049		
Extended Field Test #3 & Performance Validation II	6/10/2003	0.039	0.041	0.040	0.0395	0.0022
	6/11/2003	0.041	0.038	0.0395		
	6/12/2003	0.040	0.038	0.039		
	6/13/2003	0.036	0.043	0.0395		

The field blank results were similar to the trip blank results for EFT #2 (only 0.7% relative percent difference) and for EFT #3 (only 3.4% relative percent difference). The results for the field blanks from EFT #1 (conducted at the EPSI facility) were much higher than the trip blanks for that test (32% relative percent difference). This suggests possible contamination of Hydrar tubes at this site and is not surprising given that background mercury levels, as measured by the Jerome analyzer, were highest at the EPSI facility.

4.4 Performance Validation Study

The Performance Validation Study (PVS) was conducted to assess the performance of DTC devices over time and determine if they lose efficiency in capturing and retaining mercury after a specified period of routine operation and crushing a substantial number of lamps. This section presents the measurements collected during Phases I and II, and compares these measurements to evaluate the performance of each device. Phases I and II are separated by five months, and each DTC device, except the Manufacturer D device, was used in the EFTS during this time, crushing approximately 3,800 – 4,300 lamps at three locations.

4.4.1 Performance Validation Study - Phase I

Phase I of the PVS was conducted at the AERC facility in Ashland, Virginia (AERC Ashland) during the week of February 24, 2003. As described in Chapter 3, analytical air samples were collected to measure the concentrations of mercury in the containment structure during operation of the new DTC devices, [19] and the Jerome analyzer was used to collect direct-reading measurements.

Temperature and humidity in Richmond, Virginia for each day at this study location were obtained from an online weather service archive. The average outdoor temperatures during this testing interval ranged between 28.4 and 42.6 degrees Fahrenheit. The average outdoor relative humidity ranged between 57.5 and 99.3

[19] *The Manufacturer A device is a prototype and, therefore, is not considered a new device.*

percent. Due to the cold weather conditions, the bay doors to the outside remained closed during the tests.[20]

Background measurements of mercury vapor concentrations, as measured using Hydrar tubes, were 0.0039 mg/m^3 and 0.0047 mg/m^3. These levels were most likely due to the ongoing, high throughput volume crushing of fluorescent bulbs conducted by AERC in the adjacent bay. A large doorway connected the bay where testing was conducted and the bay where AERC operated its industrial-sized bulb crusher. The facility separated the bays by keeping a pull-down door in-between the two bays closed for the majority of testing; however, the pull-down door was opened occasionally to move materials back and forth between bays (e.g., lamps required for the test). The effect of background concentrations on study results is further discussed in Section 6.1.

In this phase of the Study, one drum of lamps was processed through each device. Table 4. 5 summarizes the number of Phillips Lighting "Alto®" lamps processed to fill one drum. The number of lamps is specific to each device.

Table 4. 5: Total Lamps Processed in Each Device, Performance Validation Study I

Device	Number of Lamps Processed	Type of Lamp
Manufacturer A	637	T-12 fluorescent (3.5-4.2 mg Hg/lamp)
Manufacturer B [a]	611	T-8 fluorescent (3.0 mg Hg/lamp)
Manufacturer B [a]	113	T-12 fluorescent (3.5-4.2 mg Hg/lamp)
Manufacturer C	706	T-12 fluorescent (3.5-4.2 mg Hg/lamp)
Manufacturer D [b]	276	T-12 fluorescent (3.5-4.2 mg Hg/lamp)

[a] Manufacturer B device processed mostly T-8 lamps due to a temporary shortage of T-12 lamps.
[b] Manufacturer D device was shut-down before processing a full drum. Refer to Section 3.5.3.

It is important to note that during PVS – Phase I, all of the lamps processed were Alto® fluorescent lamps. These lamps were specifically selected for use in Phase I because these data were also used for the Mass Balance Study, and Alto® lamps are manufactured with more precise doses of mercury than other lamps.

4.4.1.1 Analytical Air Sample Results

The results of the air samples collected during Phase I of the PVS inside the containment structure are presented in Figure 4. 1. Air sample results for the Manufacturer A, Manufacturer B, and Manufacturer C devices were generally below both the OSHA PEL and the ACGIH TLV values. The Manufacturer D device exceeded the PEL and the TLV values for seven of the eight samples collected.

For a separate graphical depiction of the analytical air sample results collected for each DTC device, refer to Appendix A, Figures 1 through 5. To review the actual results for each analytical air sample, refer to Appendix A, Table 1. The Data Chem reports are available in Appendix C.

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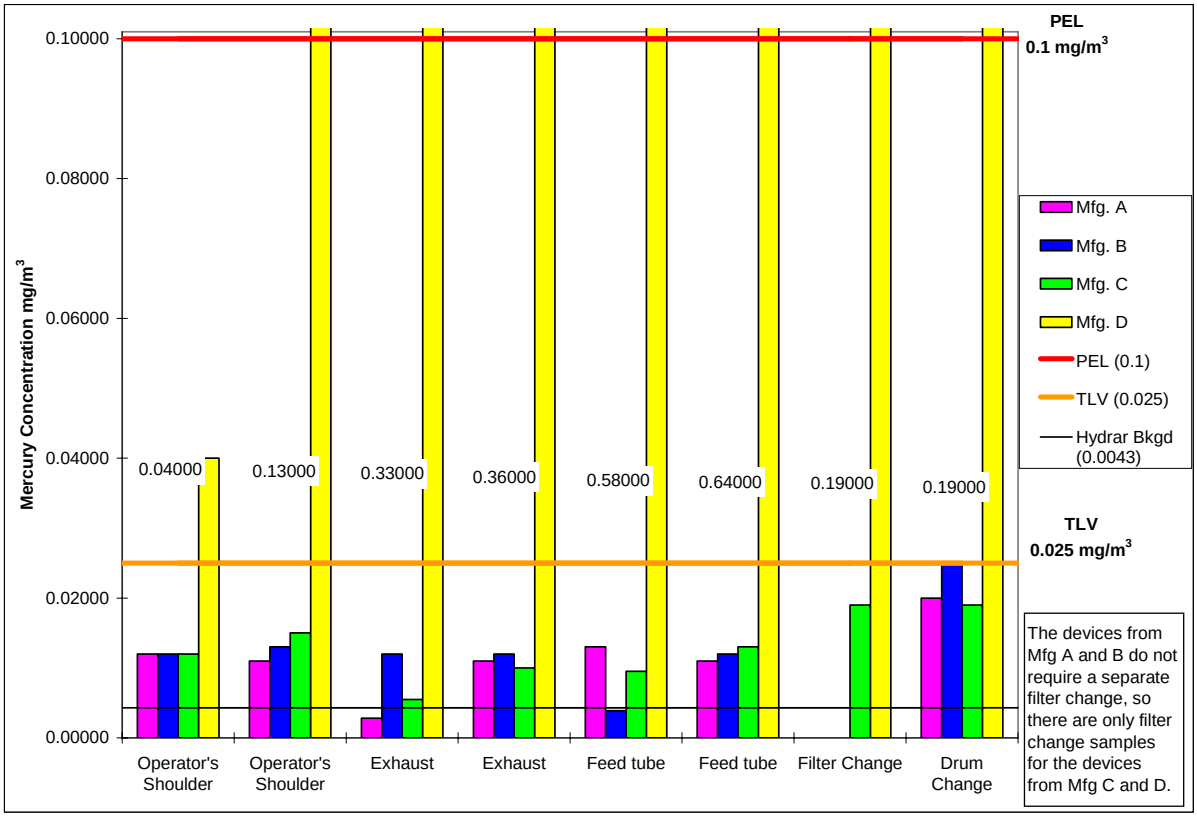
[20] *Outdoor temperature and humidity data were collected at the request of the EPA Work Group. While indoor data, when collected, better characterize the operating environment for the devices, the outdoor data are still significant.*

Figure 4. 1: Analytical Air Sampling Results, Performance Validation Study I[a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

4.4.1.2 Jerome Mercury Vapor Analyzer Results

The Jerome analyzer results from Phase I of the PVS inside the containment structure are displayed in Table 4. 6.

Table 4. 6: Jerome Analyzer Measurements - Inside Containment, Performance Validation Study I

Device	Jerome Mercury Vapor Analyzer Readings (mg/m³)		
	During Operation	Filter Change	Drum Change
Manufacturer A	0.005 – 0.009	NA [d]	0.005 – 0.009 [a]
Manufacturer B	0.007 – 0.009	NA [d]	0.026 [a]
Manufacturer C	<0.003 – 0.005	0.008 [b]	0.008 [b]
Manufacturer D	0.44 - 0.89[c]	No data [c]	No data [c]

NA – Not applicable
[a] During the drum change, the measurements were at the maximum levels recorded.
[b] During the filter change and the drum change, measurements were at the maximum levels recorded.
[c] See paragraph below and Section 3.5.3.
[d] The Manufacturer A and Manufacturer B devices do not have a separate filter change.

The real-time mercury vapor concentrations measured inside the containment structure using the Jerome analyzer during operation of the Manufacturer A, Manufacturer B, and Manufacturer C devices were all below the OSHA PEL and the ACGIH TLV values (with the exception of the Manufacturer B device during the drum change, which exceeded the TLV value). The Jerome analyzer readings

collected while operating the Manufacturer D device exhibited a continuous increase in mercury concentrations. After processing approximately 25 to 30 lamps, the Jerome analyzer measured mercury vapor at 0.44 mg/m^3, and processing was suspended to allow the operator to don respiratory protection. Crushing operations then continued for approximately 45 minutes, until the Jerome analyzer readings increased to 0.89 mg/m^3. Testing of the Manufacturer D device at this facility was permanently suspended after processing a total of 276 lamps, due to the persistent TLV and PEL exceedances in the test area. Further discussion of the Manufacturer D device is provided in Section 3.5.3.

4.4.2 Performance Validation Study – Phase II

Phase II of the PVS was conducted at AERC Ashland during the week of June 9, 2003. The Manufacturer A, Manufacturer B, and Manufacturer C devices were tested during Phase II; as noted earlier, the Manufacturer D device was removed from the Study due to airborne mercury concentrations consistently above the PEL during Phase I. The average outdoor temperature during this testing interval ranged between 70.0 and 79.0 degrees Fahrenheit, and average outdoor relative humidity ranged between 73.0 and 80.6 percent. The indoor temperature and relative humidity were measured using a Velocicalc instrument.

- Temperatures: ranged between 73.0 and 86.2 degrees Fahrenheit, with a weekly average of 81.2 degrees Fahrenheit.

- Relative humidity: ranged between 54.5 and 74.4 percent, with an average of 63.1 percent.

As described in the Sampling and Study Plan (*refer to Appendix D)*, the Phase II testing was conducted after each DTC device had processed six to seven drums' worth of lamps.

Table 4. 7 summarizes the number of lamps processed to fill one drum. The number of lamps is specific to the unique operation of each device.

Table 4. 7: Total Lamps Processed in Each Device, Performance Validation Study II

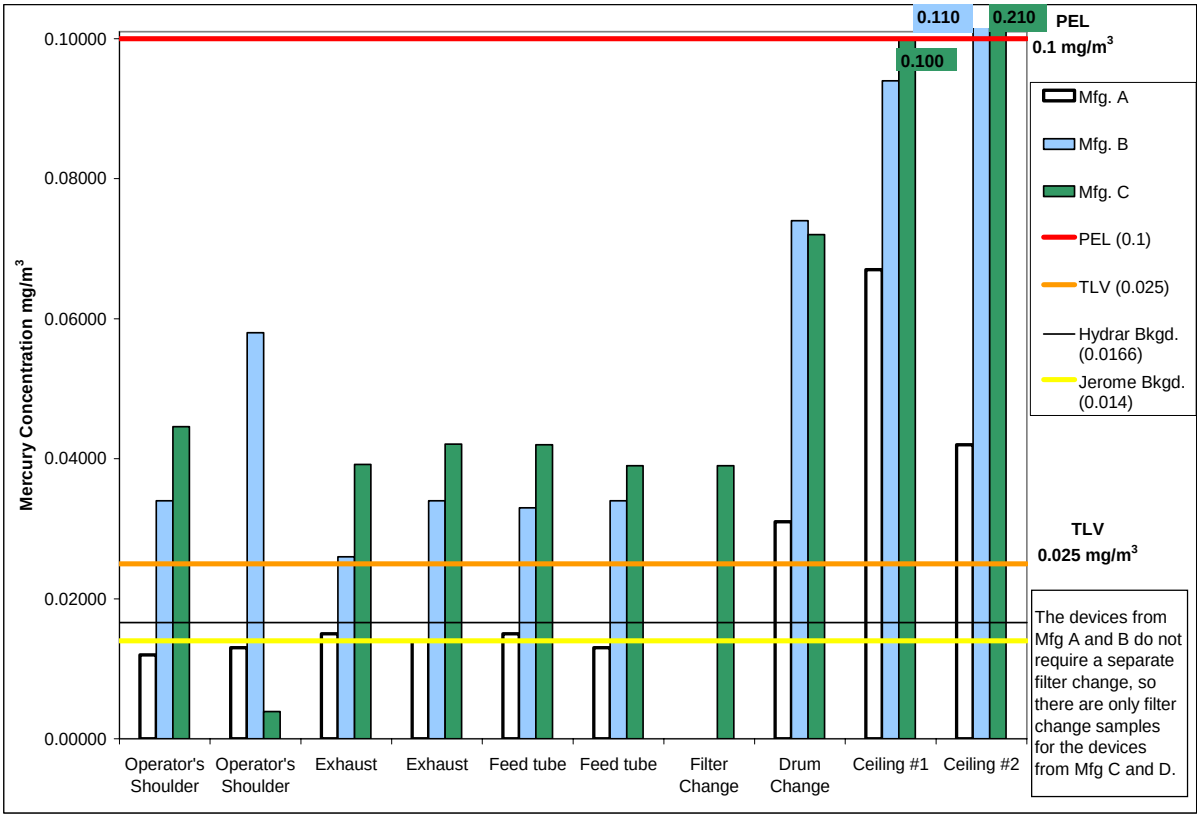
Device	Number of Lamps Processed
Manufacturer A	667
Manufacturer B	617
Manufacturer C	801

During Phase II of the PVS, some of the lamps processed were not Phillips Alto® lamps because there were not enough of them available. The inclusion of conventional lamps in the second phase of the PVS may have affected the measured mercury concentrations because most conventional fluorescent lamps contain more mercury than Alto® lamps.

4.4.2.1 Analytical Air Sample Results

For Phase II, a majority of the results for the analytical air samples were below the OSHA PEL value, but not the ACGIH TLV value, as shown below in Figure 4. 2.

Figure 4. 2: Analytical Air Sampling Results, Performance Validation Study II[a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

The Ceiling #1 sample for the Manufacturer C device met, but did not exceed, the PEL value. [21] The two samples that exceeded the PEL were two of the three Ceiling #2 samples (Manufacturer B and Manufacturer C devices). Throughout Phase II of the PVS, air sample concentrations for the Manufacturer A device were consistently lower relative to the other two devices, usually below the TLV. To review the results for each analytical air sample, refer to Appendix A, Table 1. For a separate graphical depiction of the air sample results collected for each DTC device, refer to Appendix A, Figures 6 through 9. The Data Chem reports are available in Appendix C.

4.4.2.2 Jerome Mercury Vapor Analyzer Results

The field team experienced software performance problems while attempting to record the mercury concentration on both data loggers attached to the vapor analyzers during Phase II. The only available logged readings were those from

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21 *It is important to note that the drum-change and ceiling samples are not time-weighted averages (TWA) and should not be compared to the TLV, which is a TWA. The PEL for mercury was promulgated as a ceiling value in 1971 (36 FR 10505, May 29, 1971). A memorandum to OSHA compliance personnel was issued on September 3, 1996, that directs compliance officers to issue citations only when an overexposure exceeds 0.1 mg/m³ as an 8-hour TWA.*

operation of the Manufacturer A and Manufacturer B devices inside the containment structure. Mercury vapor analyzer measurements for the Manufacturer C device were manually recorded, as time allowed. (Prior to beginning the Phase II test for the Manufacturer C device, the Jerome analyzer recorded 0.008 mg/m^3 outside the containment structure and readings between 0.009 mg/m^3 and 0.012 mg/m^3 inside the containment structure.) Refer to Table 4. 8 for the Jerome analyzer readings taken inside the containment structure during PVS – Phase II.

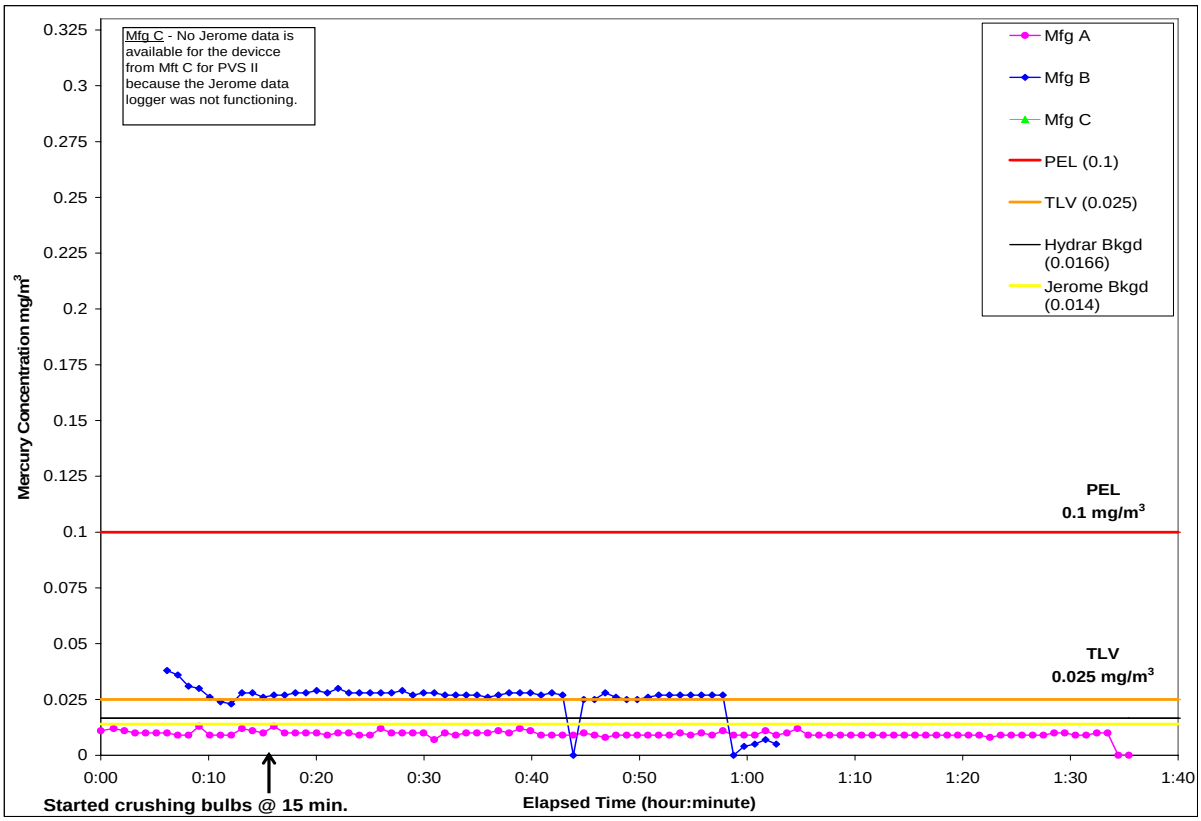
Table 4. 8: Jerome Analyzer Measurements - Inside Containment, Performance Validation Study II

Device	Jerome Mercury Vapor Analyzer Readings (mg/m^3)		
	During Operation	Filter Change	Drum Change
Manufacturer A	0.007 – 0.013	No data [a]	No data [b]
Manufacturer B	<0.003 – 0.030	No data [a]	No data [b]
Manufacturer C	0.02 – 0.04 [c]	No data [c]	No data [c]

[a] The Manufacturer A and Manufacturer B devices do not have a separate filter change.
[b] Drum was changed the following day.
[c] Values were manually recorded, as time permitted, because data logger was not functioning.
[d] Data logger was communicating with Jerome analyzer to collect samples but did not record data.

For a graphical depiction of the logged Jerome analyzer data, refer to Figure 4. 3 and Appendix A, Figures 10 through 12.

Figure 4. 3: Jerome Results - Inside Containment, Performance Validation Study II[a]

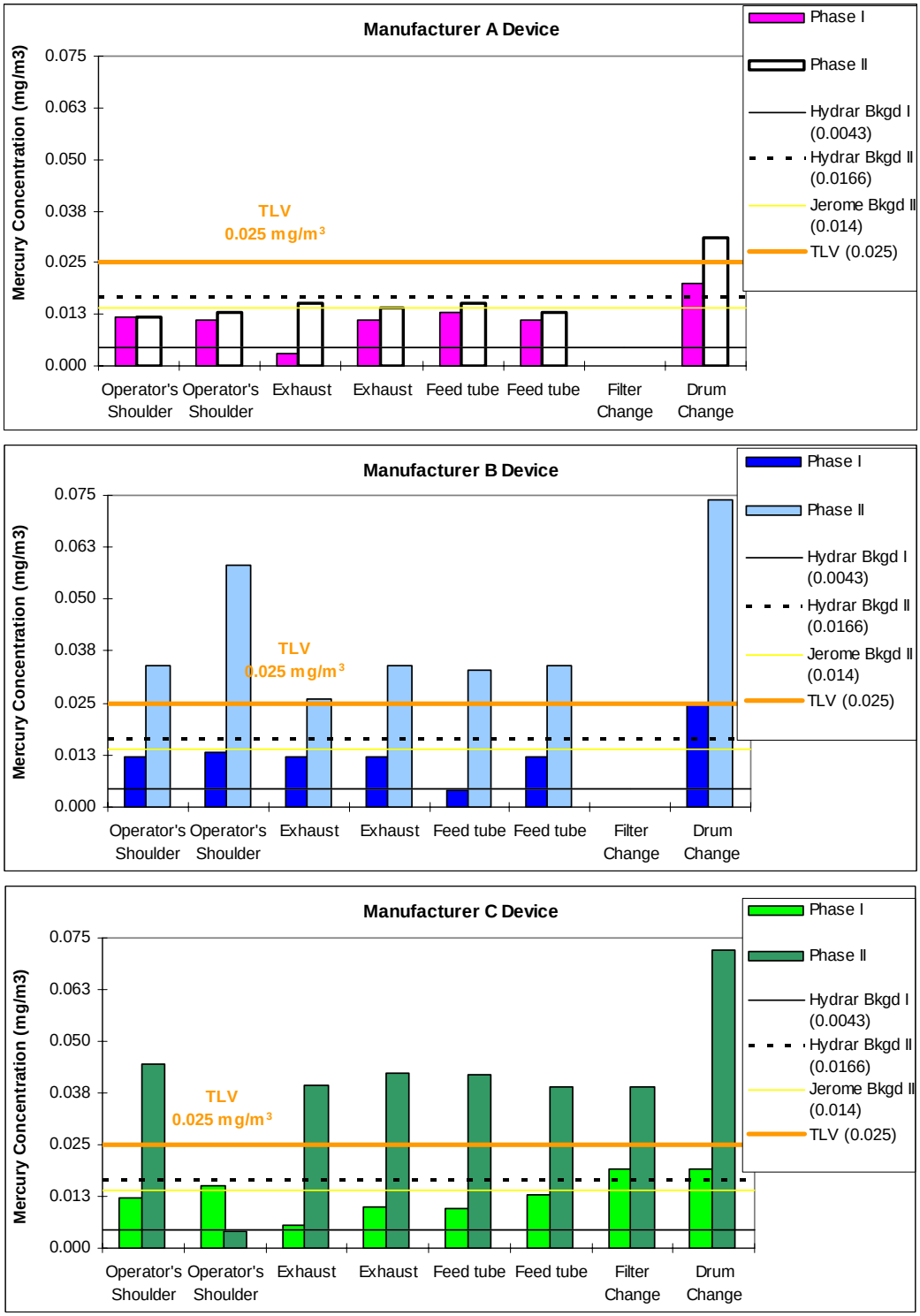


[a] The TLV is included on the graph as a point of reference. The mercury concentrations shown on this graph represent instantaneous measurements and do not represent eight-hour TWAs.

4.4.3 Comparison of Performance Validation Study Phases I and II

Overall, analytical air sample results for all three DTC devices during the PVS were higher during Phase II than Phase I (*refer to Figure 4. 4 and Figures 13, 14, and 15 in Appendix A*). The ceiling samples collected during Phase II are not included in the graphs below because no ceiling samples were collected during Phase I.

Figure 4. 4: Analytical Air Sampling Results, Performance Validation Study – Phases I & II [a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

Background mercury levels inside the AERC Ashland facility were higher during Phase II than during Phase I. Several one-way Analyses of Variance (ANOVAs) were calculated using the data from Phase I and Phase II. Table 4. 9 compares the results from the Phase I and II PVS tests to background mercury levels and to each other. The ceiling samples are not included in these comparisons because no ceiling samples were taken during Phase I.

Table 4. 9: Performance Validation Study Air Sampling Data Comparison [a, b]

Device	Significant Difference from Background Concentrations		Significant Difference between Phase I and Phase II Concentrations	
	Phase I	Phase II	Measured Value	Background Corrected Values [c]
Manufacturer A	yes p-value = 0.0782	no p-value = 0.6682	no [d] p-value = 0.1700	no [d] p-value = 0.5172
Manufacturer B	yes p-value = 0.0432	yes p-value = 0.0402	yes p-value = 0.0013	yes p-value = 0.0076
Manufacturer C	yes p-value = 0.0380	yes p-value = 0.0869	yes p-value = 0.0011	yes p-value = 0.0081

[a] Data from limited operation of the Manufacturer D device not included because of failure during Phase I.
[b] If p-value < alpha (0.1), the data being compared are significantly different from each other (90% confidence).
[c] The mean background concentration of mercury for specific Phase was subtracted from each of the concentrations measured for each of the devices during that Phase of the Study.
[d] The comparisons for the Manufacturer A device may not be valid because the concentrations of mercury measured in Phase II were not significantly different from the background concentrations; however, they are given here for reference.

As show in Figure 4. 4, the background levels measured in Phase I using the Hydrar tubes averaged 0.0043 mg/m^3, in contrast to the Phase II Hydrar tube background levels, shown in Figure 4. 5, that averaged 0.0166 mg/m^3. (Jerome readings are not comparable because no Jerome background data are available for Phase I.) During Phase I, the concentrations of mercury detected using the personal and area air samples were significantly different from the background concentrations for all three devices. During Phase II, the background concentrations were significantly different from the analytical air sample results from the Manufacturer B and Manufacturer C devices, but not significantly different from the analytical air sample results for the Manufacturer A device.

These statistical comparisons are empirically illustrated by the fact that in the second phase of the PVS, during the operation of the Manufacturer B and Manufacturer C devices, most samples exceeded the ACGIH TLV value. However, during the operation of the Manufacturer A device, all samples other than the drum change and ceiling samples were below the TLV value. The Manufacturer A device features a larger particulate filter and a larger carbon absorption bed than the other two devices. The more substantial pollution control equipment could, at least partially, explain why the PEL value was never exceeded by the Manufacturer A device during the PVS, and the TLV value was only exceeded by three samples.

A number of additional factors, external to actual device performance, may have contributed to the differences between the results for the two phases. During the

Phase II tests (performed in June 2003), the outdoor temperature was 25ºF-50ºF higher than during Phase I (performed in February 2003), which could have elevated the indoor temperature during air volume changes (e.g., doors opening). An increase in temperature, over a range of 40 to 85 degrees Fahrenheit, has been shown to cause an increase in volatilization of mercury, resulting in greater detected concentrations.[22] Moreover, the lamps processed in Phase II consisted of a mixture of the Alto® Phillips Lighting lamps (which have lower nominal quantities of mercury per lamp) and ordinary fluorescent lamps, with higher nominal mercury content, whereas the Phase I test used Alto® lamps exclusively. Additionally, the DTC devices were not decontaminated before performing the PVS – Phase II testing, so the results from Phase II may be biased high due to residual mercury that may have been in the device before the testing began. These factors may have contributed to the higher mercury vapor concentrations measured in Phase II. However, these factors may not have significantly affected the outcome of the Performance Validation Study because the results in Phase II for the device from Manufacturer A were not significantly different from the results in Phase I.

Overall, these data suggest possible deterioration in DTC device performance for the devices from Manufacturer B and Manufacturer C from Phase I to Phase II, as measured by the ambient mercury vapor concentration during device operation. For the Manufacturer C device, airborne concentrations increased by factors of between two and five, with the most notable decrease in performance indicated in the device exhaust samples and the drum change samples. For the Manufacturer B device, airborne concentrations increased by factors of between two and four, with the most notable decrease in performance indicated in the device feed tube samples and the drum change samples.

4.5 Extended Field Test Study

4.5.1 Extended Field Test #1

The first Extended Field Test (EFT #1) was conducted at the EPSI facility in Phoenix, Arizona (EPSI Phoenix), during the week of March 23, 2003. Temperature and humidity in Phoenix, AZ for each day of testing were obtained from an on-line weather service archive. The average outdoor temperatures during this testing interval ranged between 63.5 and 73.0 degrees Fahrenheit. The average outdoor relative humidity ranged between 12.1 and 31.5 percent.

As described in Chapter 3, area and personal air samples were collected using sampling pumps, and real-time vapor measurements were recorded on Jerome analyzers. Originally, all four devices were going to be tested during EFT #1. However, the Manufacturer D device testing was terminated when mercury concentrations well above the OSHA PEL value were detected in the device operator's breathing zone after processing 16 lamps. The mercury release was likely

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[22] *Refer to Raposo, Cláudio; Windomöller, Cláudio Carvalhinho; and Júnior, Walter Alves Durão. 2003. Mercury speciation in fluorescent lamps by thermal release analysis. Waste Management. 23 879-886. and Aucott, et al, 2003. Release of Mercury from Broken Fluorescent Bulbs. J. Air & Waste Manage. Assoc. 53: 143-151.*

due to the fact that the Manufacturer D device arrived at EPSI Phoenix with a large crack in the vacuum assembly (*refer to Section 3.5.3 for further discussion*).

The following table summarizes the number of lamps processed to fill each drum for the Manufacturer A, Manufacturer B, and Manufacturer C devices, by device. The Sampling and Study Plan (*refer to Appendix D*) specified that enough lamps would be crushed to fill two 55-gallon drums for each DTC device during each EFT.

Table 4. 10: Total Lamps Processed in Each Device, Extended Field Test #1

Device	Number of Lamps – 1st Drum	Number of Lamps – 2nd Drum
Manufacturer A	684	700
Manufacturer B	534	580
Manufacturer C [a]	750	336
Manufacturer D [b]	16	--

[a] Refer to Section 3.5.2 for an explanation of the differences between the 1st and 2nd drums.
[b] Refer to Section 3.5.3 for an explanation as to why the Manufacturer D device processed very few lamps.

4.5.1.1 Analytical Air Sample Results

As shown on Figure 4. 5, most of the results for analytical air samples collected during operation of the Manufacturer A, Manufacturer B, and Manufacturer C devices exceeded the ACGIH TLV value, including all samples collected in the breathing zone of the operator. A few results from these three devices also exceeded the OSHA PEL value:

- The Manufacturer A device exceeded the PEL value on a feed tube sample.[23]

- The Manufacturer B and Manufacturer C devices exceeded the PEL value in the breathing zone of the operator during the second drum change.

Consistent with the observations made during PVS – Phase I, the Manufacturer D device was unable to control its air emissions in that both samples collected in the operator's breathing zone during operation of this device exceeded the PEL value.

For a graphical depiction of the air sample results collected for each DTC device, refer to Appendix A, Figures 16 through 20. To review the actual results for each analytical air sample, refer to Appendix A, Table 1. The Data Chem reports are available in Appendix C.

One possible issue with actual mercury emissions from the DTC devices was the large number of broken lamps visually identified in the shipping boxes as they arrived at the facility. The study team suspected that boxes containing broken lamps were contaminated with mercury vapor existing in air spaces inside the corrugated matrix of the cardboard, as well as mercury particles absorbed into the cardboard. Although the broken lamps were recognized as a possible confounding factor during

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[23] *A visible leak was observed at the feed tube flange of Manufacturer A for the first drum. The cause of the leak was determined to be due to a missing flange gasket that was not installed during assembly. After the first drum was filled, the missing gasket was installed at the feed tube flange for the second drum, and the leak problem was corrected.*

EFT #1, no testing to quantify the mercury contribution of the broken lamps and assess this possibility was done until EFT #2 (the box test discussed in Section 4.6).

4.5.1.2 Jerome Mercury Vapor Analyzer Results

Review of the Jerome analyzer readings taken inside the containment structure at one-minute intervals indicated a similar pattern of measured mercury concentrations similar to the air sample analytical results (*refer to Appendix A*, *Figure 26*). Table 4. 11 presents ranges of mercury concentrations measured by both Jerome analyzers, while testing each DTC device.

Table 4. 11: Jerome Analyzer Measurements, Extended Field Test #1

Device	ACGIH TLV (mg/m^3)	OSHA PEL (mg/m^3)	Jerome Mercury Vapor Analyzer Results (mg/m^3)			
			# of Samples	Jerome #1		Jerome #2
				Range	Mean	Range [a]
Manufacturer A	0.025	0.1	212	0.017 - 0.041	0.027	0.029 - 0.060
Manufacturer B	0.025	0.1	121	0.021 - 0.102	0.049	0.026 - 0.131
Manufacturer C	0.025	0.1	140	0.036 - 0.211	0.074	0.0 – 0.102
Manufacturer D	0.025	0.1	11	0.011 - 0.406[b]	0.175	0.0 – 0.580[c]

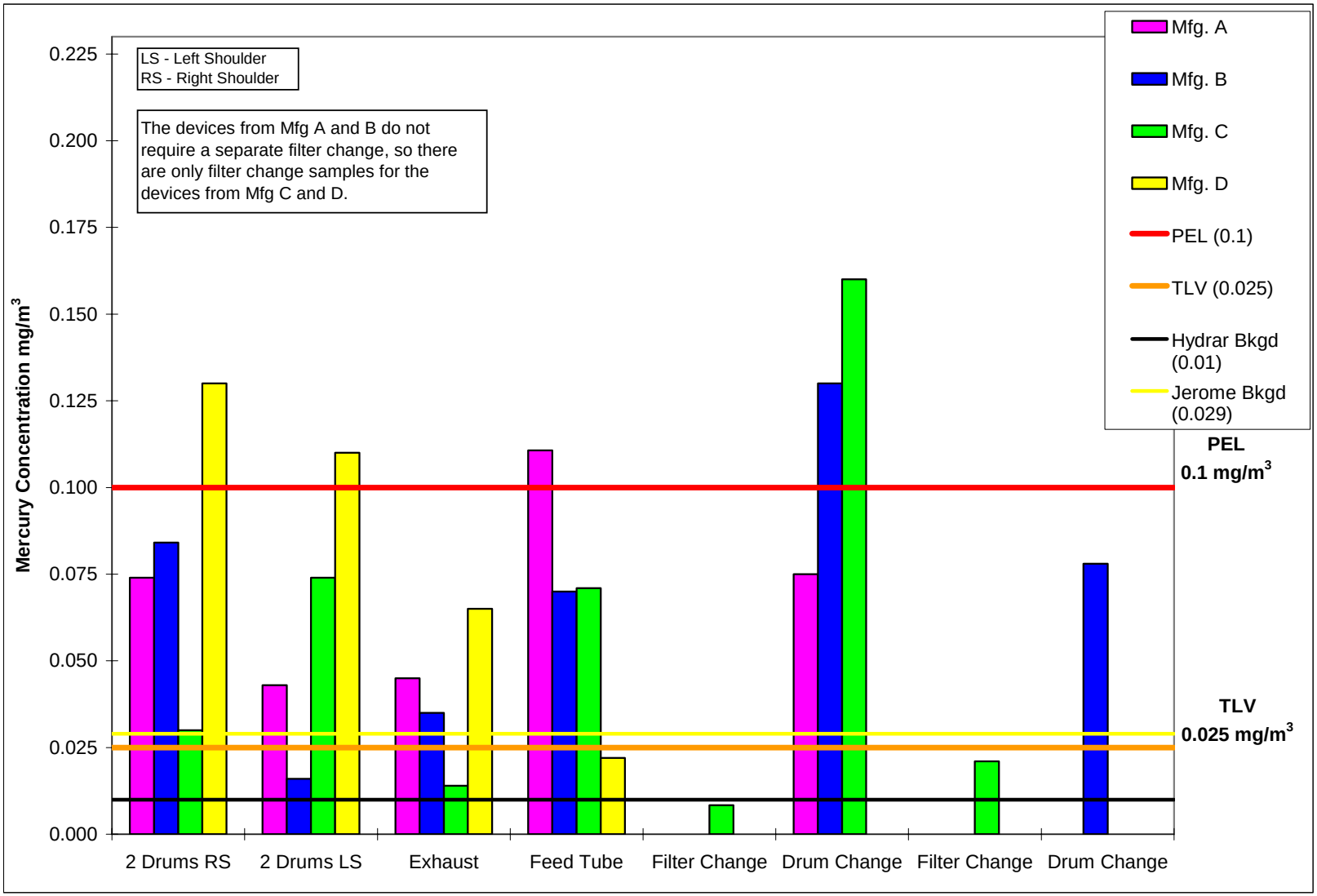
[a] Jerome #2 was used to measure the concentrations at the device exhaust, at the seal around the drum, adjacent to the feed tube, and in the operator's breathing zone.
[b] When the unit was started, the readings immediately increased to concentrations above the PEL, and testing was concluded after processing only 16 fluorescent lamps.
[c] Jerome #2 was stationed inside the containment structure and recorded similar readings above the PEL.

Mercury concentrations in the ambient air in the headspace of a representative drum of crushed lamps were also measured using the Jerome analyzer. This activity was not in the Sampling and Study Plan, but was added in the field. Not unexpectedly, a headspace reading of 0.909 mg/m^3 was registered above a full drum immediately after the DTC device was removed from on top of the drum. A reading taken next to the drum after removing the DTC device from the top of the drum and affixing the drum lid was considerably lower, as expected (0.03 mg/m^3).

While operating the Manufacturer C device, some operational difficulties delayed the start of testing and may have had an effect on the concentrations measured on the Jerome analyzers *(refer to Section 3.5.2 for further discussion regarding the operational problems)*. The Jerome results were above the TLV value and below the PEL value at the beginning, but increased to exceed the PEL value toward the end of testing. During the first drum change, the Jerome readings inside the containment structure slightly exceeded the PEL value; once the drum was changed, readings reverted to levels between the TLV and PEL values. During the second drum change, readings were already elevated above the PEL value, and the test was therefore terminated.

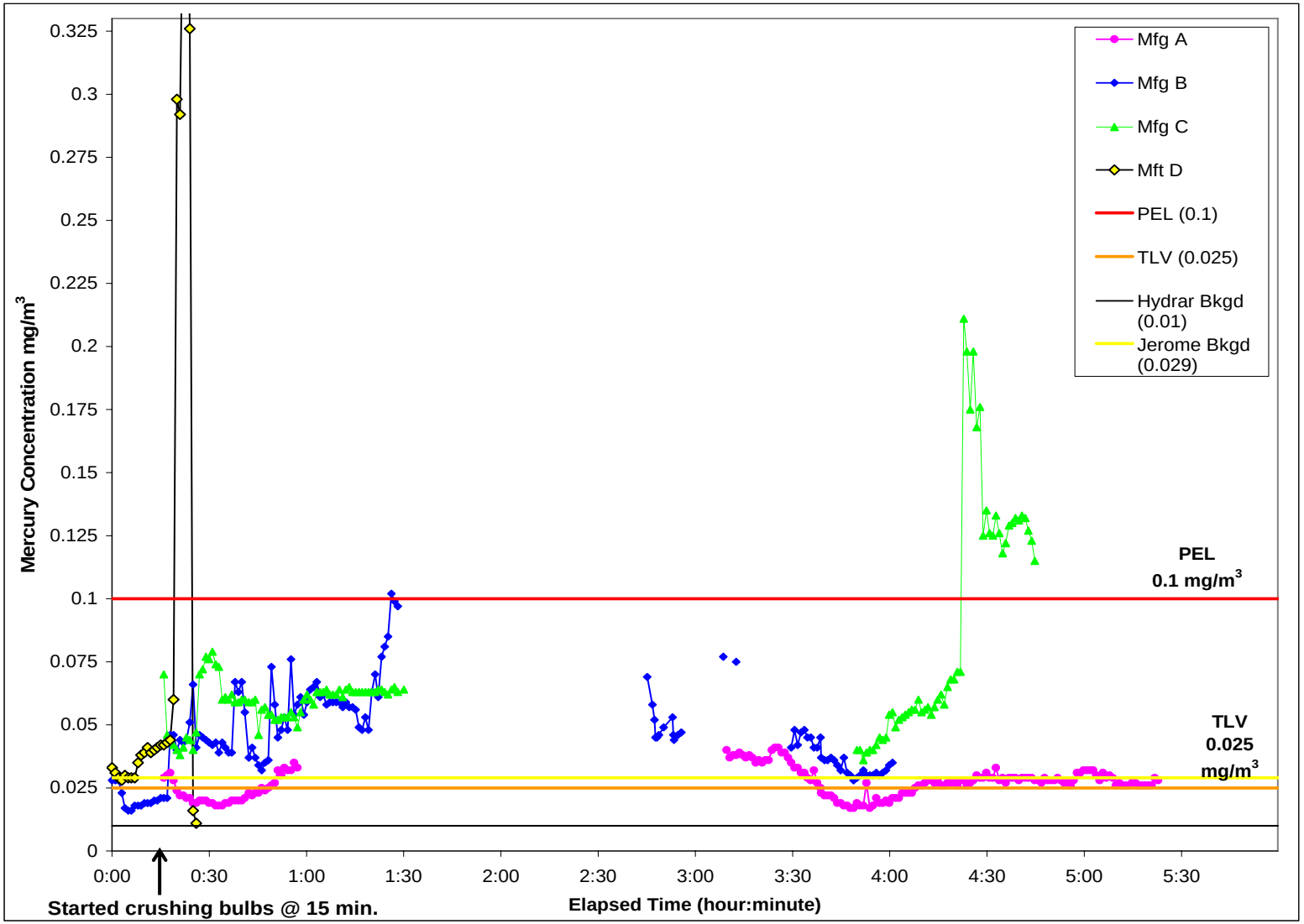
For a graphical depiction of each measurement, refer to Figure 4. 6 and Appendix A, Figures 21 through 25. The graphs also include significant milestones encountered during the device operation to better understand and interpret the measurements.

Figure 4. 5: Analytic Air Sampling Results, All Devices, Extended Field Test #1[a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

Figure 4. 6: Jerome Results – Inside the Containment, Extended Field Test #1[a]



[a] The TLV is included on the graph as a point of reference. The mercury concentrations shown on this graph represent instantaneous measurements and do not represent eight-hour TWAs.

4.5.2 Extended Field Test #2

The second Extended Field Test (EFT #2) was conducted at the AERC facility in Melbourne, Florida (AERC Melbourne) during the week of April 28, 2003. The temperature and relative humidity was measured using a Velocicalc instrument. The average outdoor temperatures during this testing interval ranged between 73.6 and 77.4 degrees Fahrenheit. The average outdoor relative humidity ranged between 73.9 and 84.4 percent. Indoor temperatures and relative humidity were also measured and recorded during this test and were as follows:

- Temperatures: ranged between 80.1 and 89.4 degrees Fahrenheit, with an average of 84.9 degrees Fahrenheit.

- Relative humidity: ranged between 68 and 85.5 percent, with an average of 75.2 percent.

As described in Chapter 3, analytical air samples were collected with sample pumps and Jerome analyzers. DTC devices from Manufacturer A, Manufacturer B, and Manufacturer C were tested during the EFTS at AERC Melbourne. Table 4. 12 summarizes the number of lamps processed to fill each drum, by device. The number of lamps is specific to the unique operation of each device.

Table 4. 12: Total Lamps Processing in Each Device, Extended Field Test #2

Device	Number of Lamps – 1st Drum	Number of Lamps - 2nd Drum
Manufacturer A	721	678
Manufacturer B #1 [a]	658	609
Manufacturer B #2 [a]	554	--
Manufacturer C	660	639

[a] Refer to Section 3.5.1.

4.5.2.1 Air Sample Results

Several analytical air sample results collected for all three DTC devices during EFT #2 exceeded the OSHA PEL value, and most of the samples exceeded the ACGIH TLV value *(refer to Figure 4. 7)*.[24]

For the Manufacturer A device, the sample on the operator's right shoulder, collected while filling the first drum, exceeded the TLV value. Also, the two ceiling samples exceeded the PEL value.

For the Manufacturer B device, the only sample collected that did not exceed the TLV value was the one collected during the first drum change. Both ceiling samples taken during the first test of the Manufacturer B device were above the PEL value. No ceiling samples were taken during the second Manufacturer B test. Six personal

[24] *It is important to note that the drum-change and ceiling samples are not time-weighted averages (TWA) and should not be compared to the TLV, which is a TWA. The PEL for mercury was promulgated as a ceiling value in 1971 (36 FR 10505, May 29, 1971). A memorandum to OSHA compliance personnel was issued on September 3, 1996, that directs compliance officers to issue citations only when an overexposure exceeds 0.1 mg/m^3 as an 8-hour TWA.*

and area air samples were collected during Manufacturer B test #1, and five were collected during Manufacturer B test #2. For the first test, four of these samples were above the PEL value, while only one sample was above the PEL value during the second Manufacturer B test (*refer to Section 3.5.1 for a description of the two tests*).

The samples that exceeded the PEL value during the first test of the Manufacturer B device included both operator shoulder samples collected during filling of first drum, the exhaust area sample during filling of two drums, and the feed tube area sample during filling of two drums. The only sample that exceeded the PEL value during the second test of the Manufacturer B device was the drum change sample.

For the Manufacturer C device, the only sample that did not exceed the TLV value was the one collected on the operator's right shoulder, while filling the first drum. The first drum change sample and both ceiling samples exceeded the PEL value.

For a graphical depiction of the air sample results collected for each DTC device, refer to Appendix A, Figures 27 through 30. To review the actual results for each analytical air sample, refer to Appendix A, Table 1. The Data Chem reports are available in Appendix C.

4.5.2.2 Jerome Mercury Vapor Analyzer Results

Review of the Jerome analyzer readings taken at one-minute intervals indicated a pattern of concentrations similar to the air sample analytical results (*refer to Appendix A*, *Figure 35*).

The Jerome analyzer was also used to take direct readings of ambient air in the headspace of a representative drum of crushed lamps. This activity was not in the Sampling and Study Plan but was added in the field. A headspace reading of 0.619 mg/m^3 was registered above a full drum on the morning after lamp crushing, and a reading of off-scale (>0.999 mg/m^3) was registered above a full drum immediately after filling the drum. (These data do not directly relate to operator health and safety because they were not measurements of the air in or near the operator breathing zone.) Table 4. 13 presents the range of mercury concentrations detected by both Jerome analyzers for each device during EFT #2.

Table 4. 13: Jerome Analyzer Measurements, Extended Field Test #2

Device	ACGIH TLV (mg/m^3)	OSHA PEL (mg/m^3)	Jerome Mercury Vapor Analyzer Results (mg/m^3)			
			# of Samples	Jerome #1		Jerome #2
				Range	Mean	Range
Manufacturer A	0.025	0.1	347	0.003 – 0.046	0.013	0.006 – 0.06[a]
Manufacturer B #1	0.025	0.1	296	0.00 – 0.328	0.078	0.004 – 0.045[c]
Manufacturer B #2	0.025	0.1	74	0.021 – 0.177	0.066	0.004 – 0.017[b]
Manufacturer C	0.025	0.1	430	0.008 – 0.128	0.034	0.008 – 0.154[c]

[a] Jerome #2 was used to measure concentrations outside the containment structure, the operator's breathing zone, the device exhaust, and at the feed tube connection to the device.
[b] Jerome #2 was used to measure concentrations outside the containment structure.
[c] Jerome #2 was used to measure concentrations outside the containment structure, in the operator's breathing zone, at the device exhaust, and on top of the device.

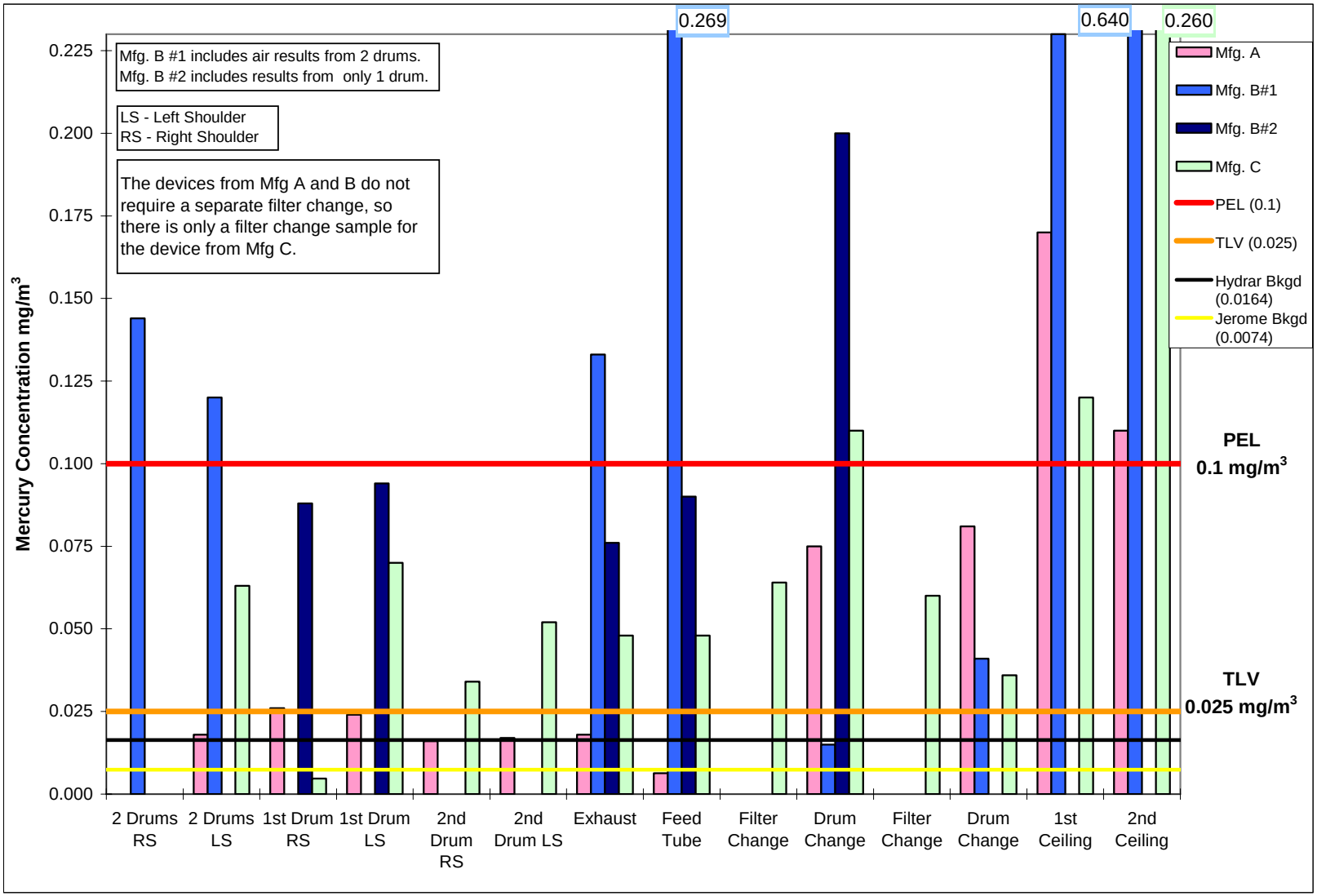
Most of the Jerome readings taken inside the containment structure for the Manufacturer A unit were below the TLV value, with no readings inside the containment structure above the PEL value. The highest reading (0.046 mg/m^3) was measured during the first drum change. The average concentration was 0.013 mg/m^3. Most readings for the Jerome analyzer located outside the containment structure were below the TLV value, and none exceeded the PEL value.

For the Manufacturer B #1 test, the readings from the Jerome analyzer located inside the containment structure were consistently above the TLV and PEL values. In contrast, most of the readings taken with the Jerome analyzer inside the containment structure during the Manufacturer B #2 test were above the TLV value, but below the PEL value. When the drum was changed during the Manufacturer B #2 test, levels inside the containment structure began to exceed the PEL value.

While bulbs were being crushed in the Manufacturer C device, the readings inside the containment structure were consistently above the TLV value but remained below the PEL value, with the exception of the reading taken during the third filter change. The highest reading (0.154 mg/m^3) was obtained after the third filter change and adjacent to a full drum of crushed lamps. The average Jerome analyzer reading inside the containment structure was 0.034 mg/m^3. Measurements recorded by the Jerome analyzer outside the containment structure were below both the TLV and the PEL values and generally did not exceed 0.010 mg/m^3.

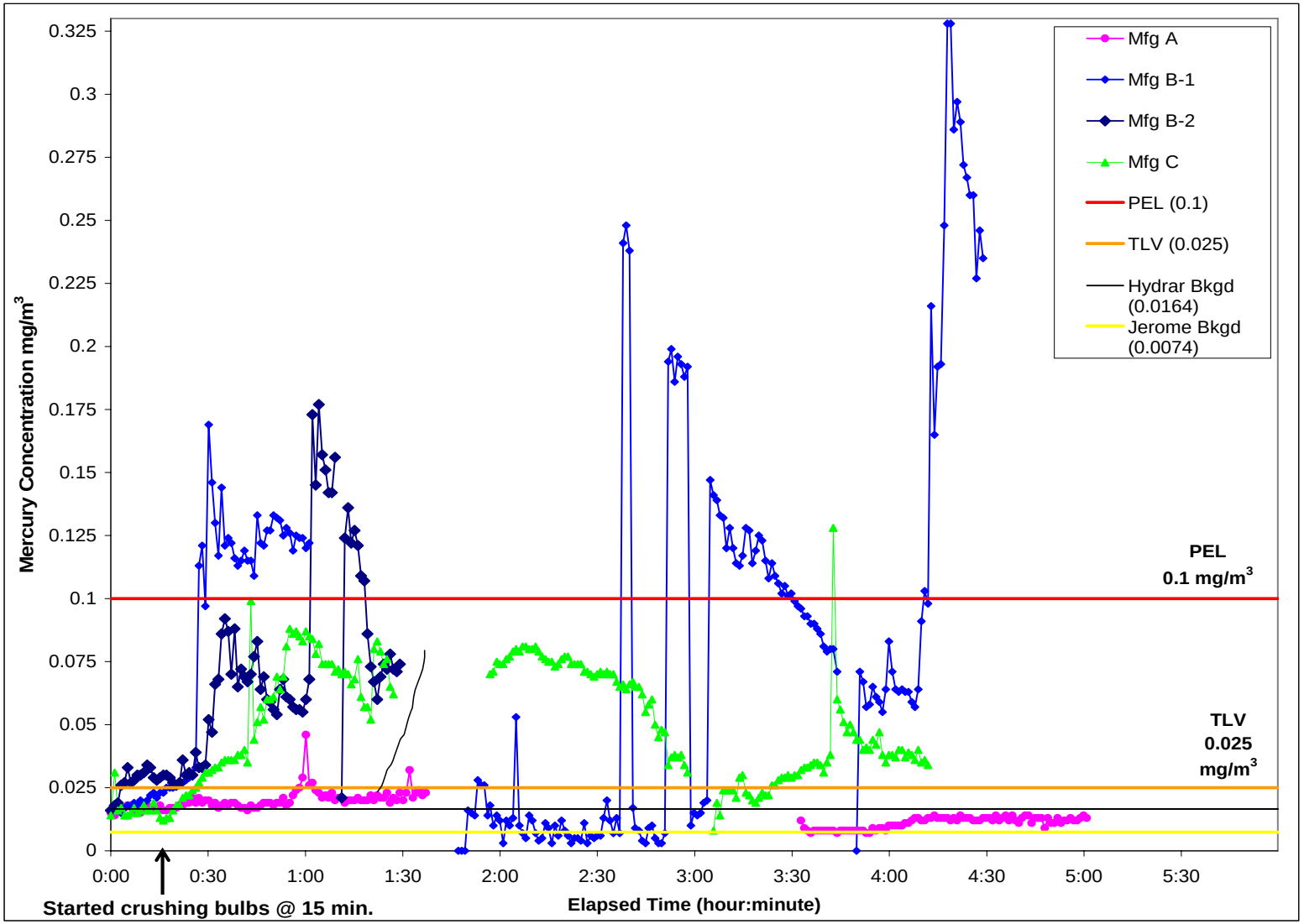
For a graphical depiction of each measurement refer to Figure 4. 8 and Appendix A, Figures 31 through 34. The graphs also include significant milestones encountered during the operation of the devices to better understand and interpret the measurements.

Figure 4. 7: Analytic Air Sampling Results, All Devices, Extended Field Test #2[a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

Figure 4. 8: Jerome Results – Inside the Containment, Extended Field Test #2[a]



[a] The TLV is included on the graph as a point of reference. The mercury concentrations shown on this graph represent instantaneous measurements and do not represent eight-hour TWAs.

4.5.3 Extended Field Test #3

EFT #3 was conducted at AERC Ashland during the week of June 9, 2003. The average outdoor temperatures during this testing interval ranged between 70.0 and 79.0 degrees Fahrenheit. The average outdoor relative humidity ranged between 73.0 and 80.6 percent. The indoor temperature and relative humidity were measured using a Velocicalc instrument.

- Temperatures: ranged between 73.0 and 86.2 degrees Fahrenheit, with a weekly average of 81.2 degrees Fahrenheit.

- Relative humidity: ranged between 54.5 and 74.4 percent, with an average of 63.1 percent.

As described in Chapter 3, ambient mercury concentrations were measured using sample pumps and Jerome analyzers, and wipe samples were collected inside the containment structure on nine surfaces for the Mass Balance Study (*refer to Appendix F for wipe sample results*). DTC devices from the following manufacturers were tested during EFT #3: Manufacturer A, Manufacturer B, and Manufacturer C. Table 4. 14 summarizes the number of lamps processed to fill each drum, by device. The number of lamps is specific to the unique operation of each device.

Table 4. 14: Total Lamps Processed in Each Device During Extended Field Test #3

Device	Number of Lamps - 1st Drum	Number of Lamps – 2nd Drum
Manufacturer A	767	719
Manufacturer B	594	539
Manufacturer C	794	689

4.5.3.1 Air Sample Results

The air sampling results from the Manufacturer B and Manufacturer C devices were consistently greater than the ACGIH TLV value *(refer to Figure 4. 9)*. Air sampling results also indicated that the Manufacturer C device and, to a lesser extent, the Manufacturer B device were prone to excursions above the OSHA PEL value during EFT #3. This occurred most frequently during drum changes and in ceiling samples. With the exception of one sample for the Manufacturer B device, the air samples within the operator's breathing zone (shoulder samples) were the TLV and PEL values during the Manufacturer B and Manufacturer C tests. In contrast, during the Manufacturer A test, breathing zone concentrations remained below the TLV value. [25] No samples taken during the Manufacturer A test exceeded the PEL value.

For a graphical depiction of the air samples collected for each DTC device, refer to Appendix A, Figures 36 through 39. To review the actual results for each analytical

[25] *It is important to note that the drum-change and ceiling samples are not time-weighted averages (TWA) and should not be compared to the TLV, which is a TWA. The PEL for mercury was promulgated as a ceiling value in 1971 (36 FR 10505, May 29, 1971). A memorandum to OSHA compliance personnel was issued on September 3, 1996, that directs compliance officers to issue citations only when an overexposure exceeds 0.1 mg/m^3 as an 8-hour TWA.*

air sample, refer to Appendix A, Table 1. The Data Chem reports are available in Appendix C.

4.5.3.2 Jerome Mercury Analyzer Results

The field team experienced software performance problems while attempting to record the mercury concentration on both data loggers attached to the vapor analyzers during EFT #3. During testing of the first device (from Manufacturer A), the Jerome analyzer appeared to be communicating properly with the data logger (i.e., it was automatically collecting samples at one minute intervals); however, upon downloading the data from the data logger, it was discovered that the data logger had not recorded any measurements. Therefore, there are no logged readings or manual readings for the Jerome analyzer for the Manufacturer A device for EFT #3. Also, due to time constraints, the study team was not able to take readings of the mercury concentration in the head space of a full drum as was done previously.

Review of the Jerome analyzer readings indicate a similar pattern of measured mercury concentrations, compared with the analytical air sample results (*refer to Appendix A, Figure 43*). Table 4. 15 presents a range of results from both Jerome analyzers for the devices from Manufacturer B and Manufacturer C.

Table 4. 15: Jerome Analyzer Measurements, Extended Field Test #3

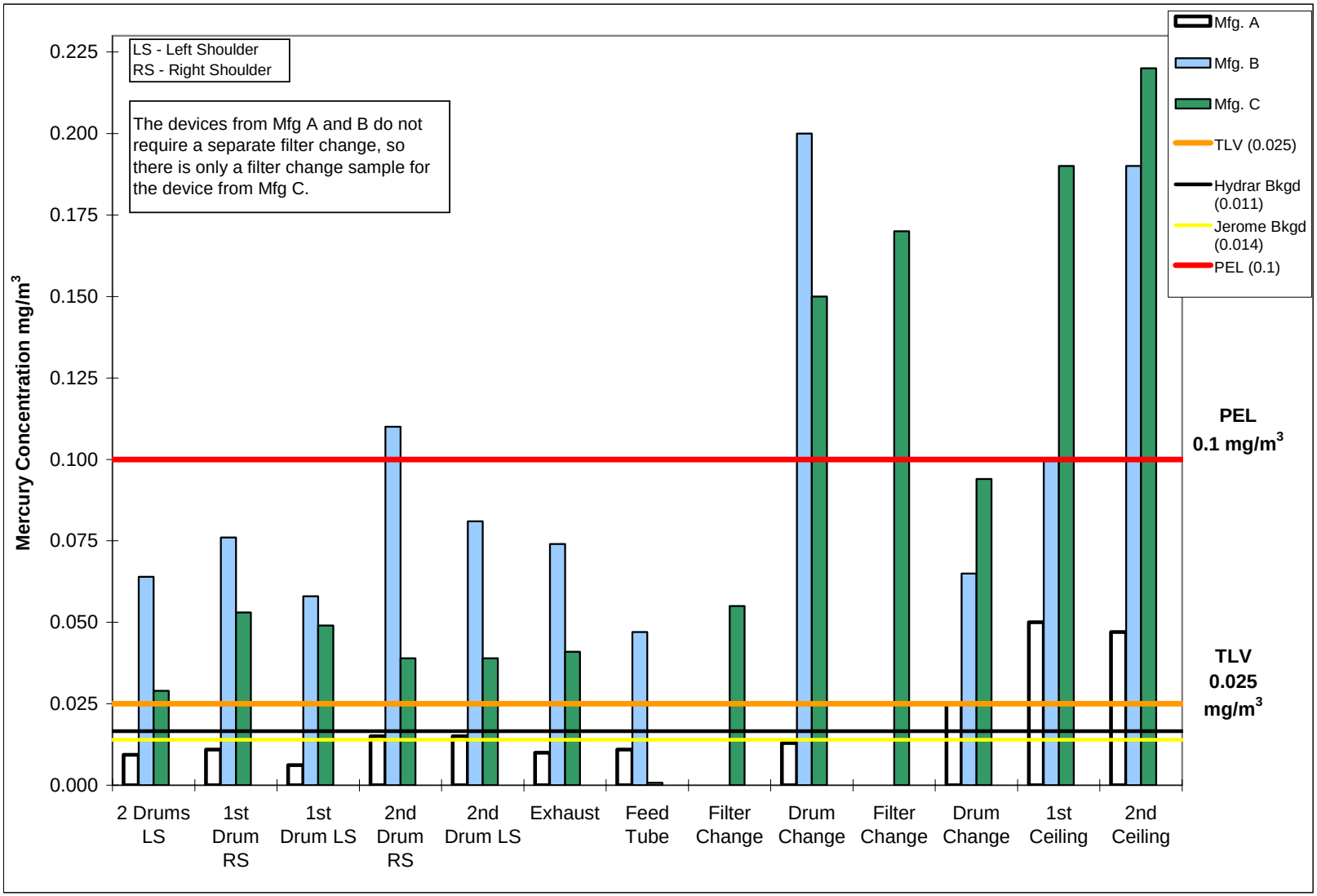
Device	AGCIH TLV (mg/m^3)	OSHA PEL (mg/m^3)	Mercury Vapor Analyzer Results (mg/m^3)			
			# of Samples	Jerome #1		Jerome #2[a]
				Range	Mean	Range
Manufacturer B	0.025	0.1	234	0.009 – 0.258	0.051	<0.003 – 0.017
Manufacturer C	0.025	0.1	218	0.008 – 0.121	0.040	0.008 – 0.02

[a] Jerome #2 unit was kept outside of the containment structure during EFT #3.

For the Manufacturer B device, most measurements (except right after startup) were above the TLV value. There were two sets of excursions above the PEL value. After approximately one hour of operation, readings increased to a maximum of 0.26 mg/m^3 and remained above the PEL value until the first drum change (10 readings within nine minutes). After the drum change, a total of four exceedances were recorded before levels dropped to between the PEL and TLV values and then stabilized. Just before the second drum change, a reading of 0.13 mg/m^3 was registered. After the second drum change, all levels remained below the PEL value and stabilized in a range just above the TLV value, until the conclusion of the test. During operation of the Manufacturer C device, nearly all of the readings (except right after startup, including startup after the first drum change) were above the TLV value. There was also a brief excursion above the PEL value, three readings within an eight-minute period, right before the first drum change. The highest reading registered during this period was 0.12 mg/m^3.

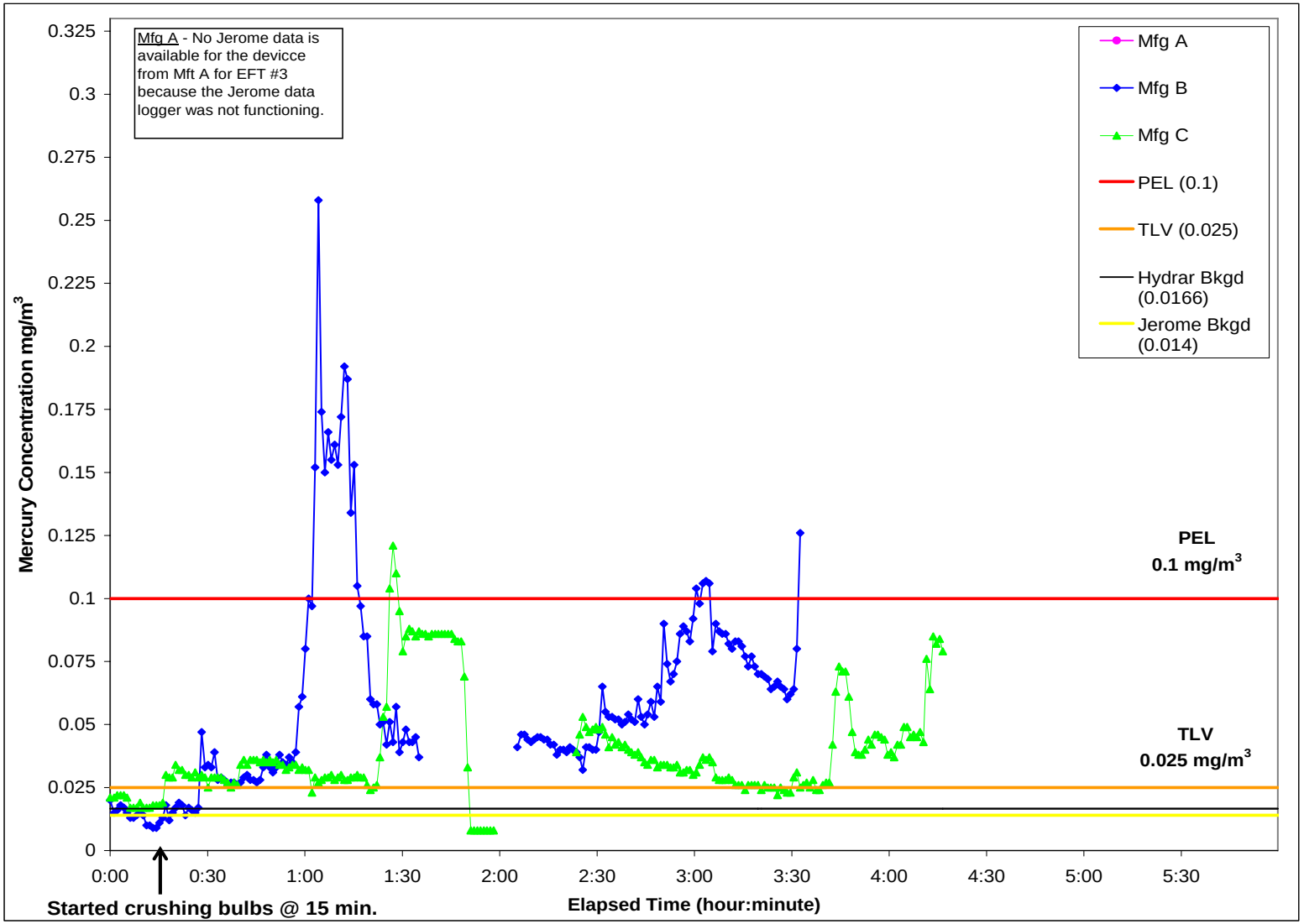
For a graphical depiction of each measurement, refer to Figure 4. 10 and Appendix A, Figures 40 through 42. The graphs also include significant milestones encountered during the operation of the devices to better understand and interpret the measurements.

Figure 4. 9: Analytical Air Sampling Results, All Devices, Extended Field Test #3 [a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

Figure 4. 10: Jerome Results – Inside the Containment, Extended Field Test #3 [a]



[a] The TLV is included on the graph as a point of reference. The mercury concentrations shown on this graph represent instantaneous measurements and do not represent eight-hour TWAs.

4.5.4 Comparison of Extended Field Tests

The EFTS was designed to evaluate the mercury vapor capture efficiency of each DTC device in a simulated occupational environment, with a focus on assessing the potential for human exposure to mercury as a result of DTC use.

Unlike the PVS, there were not extreme differences in outside air temperature during the EFTS. The range of outside air temperatures was 63.5°F-79.0°F. This may have reduced the potential variation in test results due to increased volatilization of mercury at increased temperatures (*as discussed in Section 4.4.3*). At EPSI Phoenix, testing was conducted in the same bay as the facility's industrial size lamp crusher. As a result, there was an elevated background concentration of mercury vapor in the bay, most likely due to the ongoing crushing of fluorescent bulbs being conducted by EPSI. The mean background samples collected using the air sample pumps and using Jerome #2 are shown in Table 4. 16.

Table 4. 16: Mean Background Mercury Concentrations, Extended Field Test Study

Facility	Air Samples (mg/m^3)	Jerome Samples (mg/m^3)
EPSI Phoenix (EFT #1)	0.010	0.029
AERC Melbourne (EFT #2)	0.0164	0.007
AERC Ashland (EFT #3)	0.0166	0.014

Based on single-factor ANOVAs calculated for each device at each site, the concentrations measured during operation of each device were significantly different from background concentrations in all cases (95 percent confidence), except the Manufacturer A test at AERC Ashland (EFT #1).

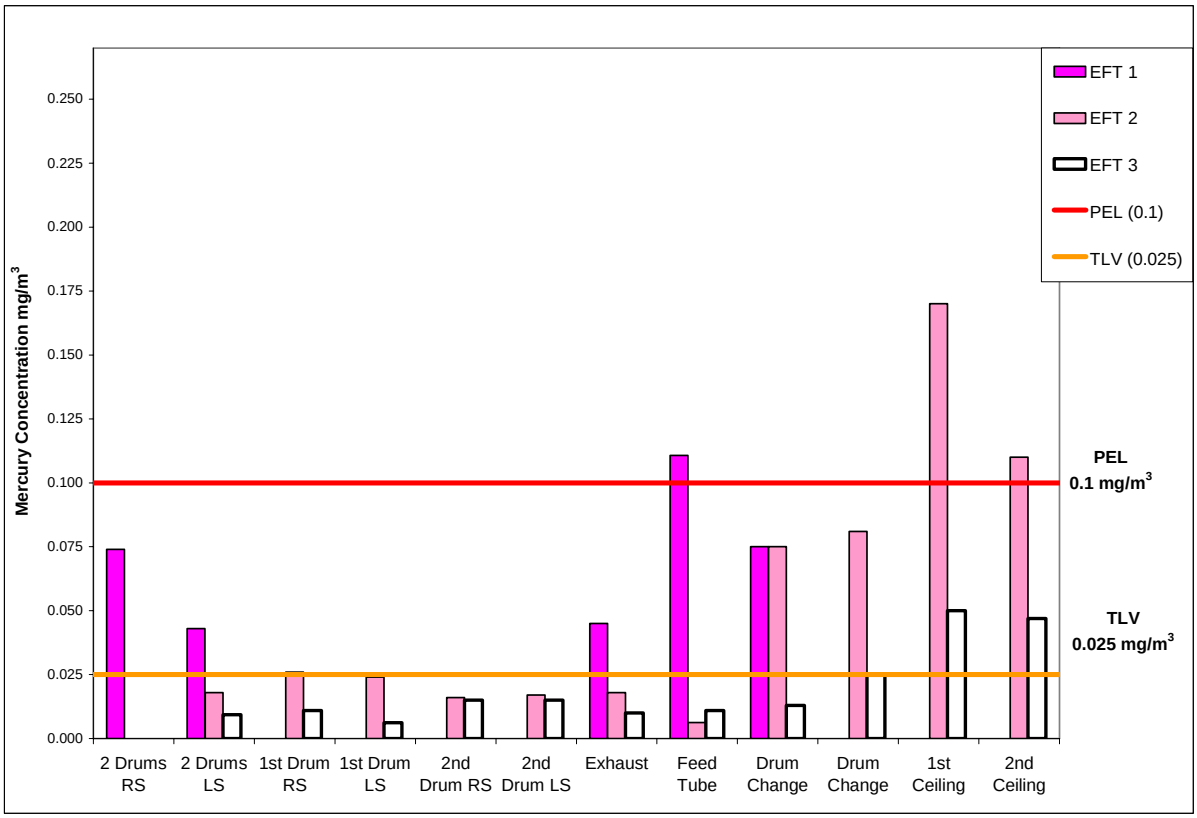
Comparison Across Devices

Devices were compared to each other for each EFT. During EFT #1 and EFT#2, there was no significant difference among the results from the analytical air samples (Hydrar tubes) collected inside the containment structure when each of the three devices were being operated. However, during EFT #3, the results from the analytical air sample collected while operating the Manufacturer A device were significantly lower than those collected while operating Manufacturer B or Manufacturer C devices (95 percent confidence). There was no significant difference between the Manufacturer B device and the Manufacturer C device during EFT #3. Figure 4. 5, Figure 4. 7, and Figure 4. 9 show the results for each EFT.

Performance of Each Device

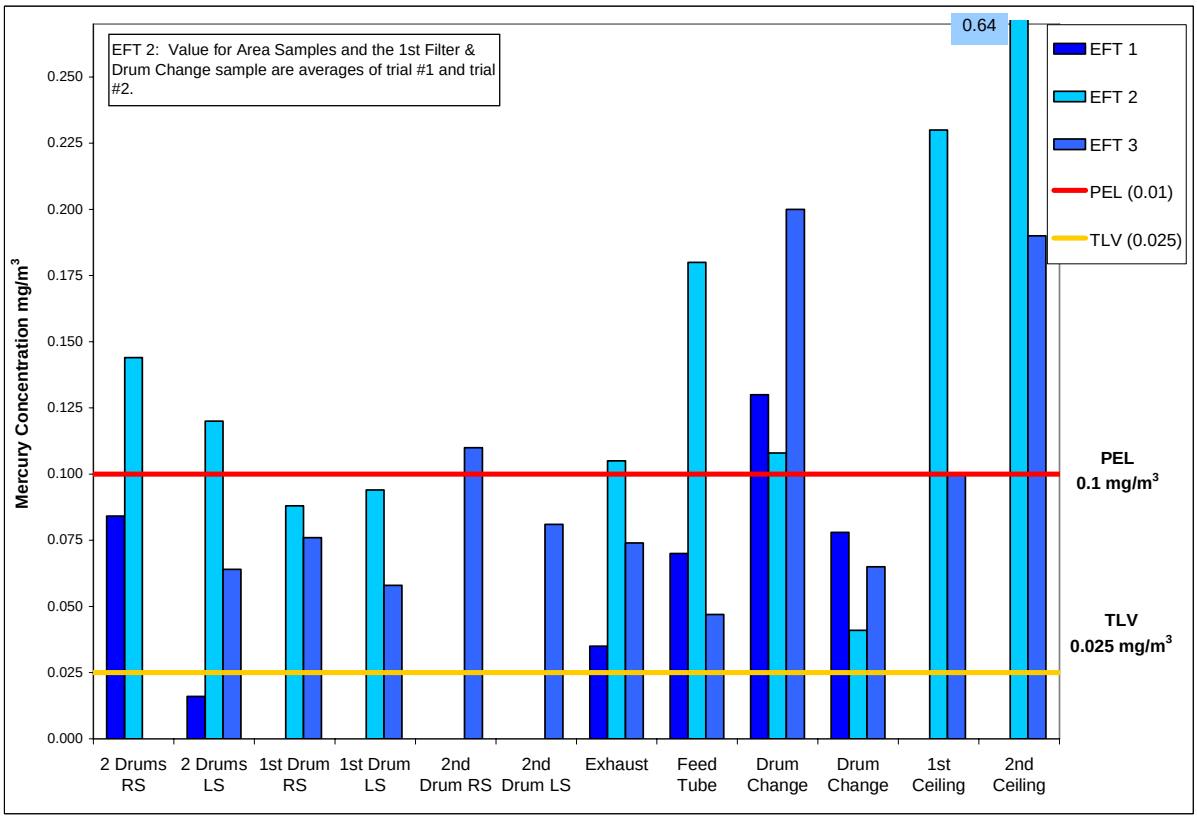
The variability of performance for each device was assessed by comparing the measured mercury concentrations from each field test; Figure 4. 11, Figure 4. 12, and Figure 4. 13 show the results from the EFTS for the devices from Manufacturer A, Manufacturer B, and Manufacturer C.

Figure 4. 11: Analytical Air Sampling Results, Extended Field Test Study - Manufacturer A [a]



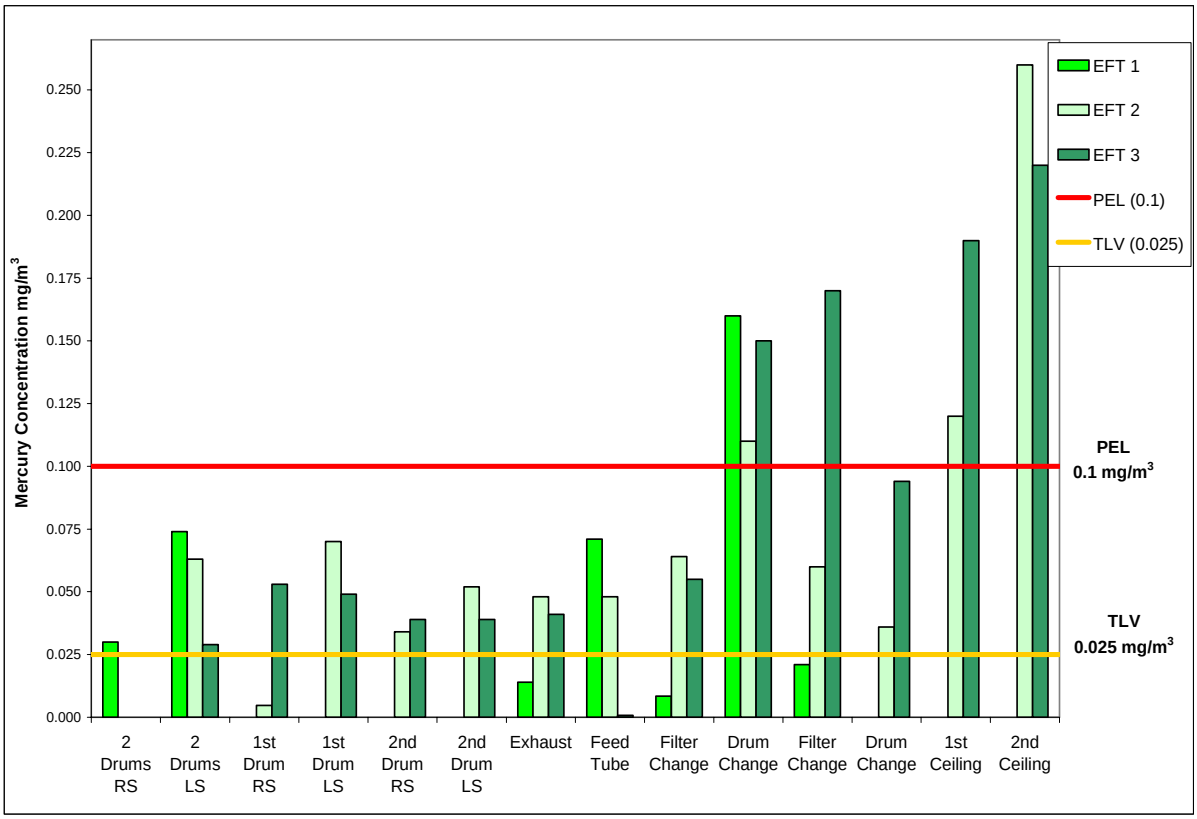
[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

Figure 4. 12: Analytical Air Sampling Results, Extended Field Test Study - Manufacturer B [a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

Figure 4. 13: Analytical Air Sampling Results, Extended Field Test Study - Manufacturer C [a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

In comparing performance over time (i.e., EFT #1, EFT #2, and EFT #3), not all of the air samples could be included. This was because no ceiling samples were taken for EFT #1. The ceiling samples were designed to assess maximum operator exposure. Therefore, inclusion of the samples would skew any statistical comparisons. Comparisons were based on the personal samples during operation and during filter changes and drum changes, the area samples within the containment structure, and the overnight samples within the containment structure (*refer to Section 4.7*).

The Manufacturer A device had significantly poorer performance during EFT #1 than during EFT #2 and EFT #3 (95 percent confidence). This was most likely due to a problem with assembly of the device in that test (*refer to footnote 23 in Section 4.5.1.1*). There was no significant difference in the performance of the Manufacturer B device or the Manufacturer C device during the EFTS.

4.6 Box Tests

During the first two portions of the Study (PVS I and EFT #1), the study team recognized that lamps that were broken in their shipping boxes could contribute mercury to the air in the containment structure during operation of the DTC devices and confound the air sample results. In order to evaluate and quantify the contribution of mercury to ambient mercury concentrations inside the containment structure by broken lamps, air samples were collected at AERC Melbourne and AERC Ashland, during EFT #2 and EFT #3, respectively.

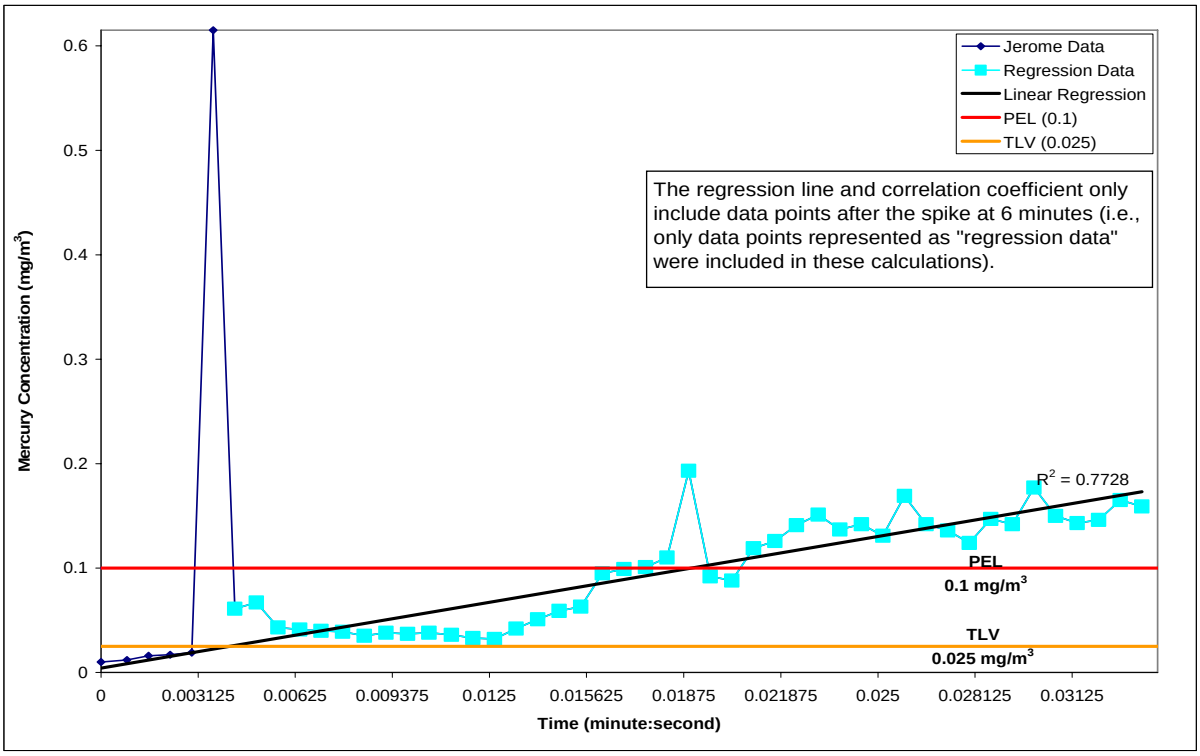
4.6.1 AERC Melbourne Box Test

As described in Section 3.5.1, the Manufacturer B device was tested twice during EFT #2. The first test was performed with boxes of broken lamps inside the containment structure, while the second test was performed without the boxes of broken lamps inside the containment structure. During both tests, personal air samples were collected during drum filling and drum changes, and area samples were collected near the device exhaust and near the device feed tube.

Four out of six sample results collected during the Manufacturer B #1 test exceeded the PEL value, and one out of the five sample results collected during the Manufacturer B #2 test exceeded the PEL value. The fact that 66.7 percent of the samples in test #1, when there were boxes with broken bulbs inside the containment structure, exceeded the PEL value, while only 20 percent of the samples in test #2, when there were not boxes inside the containment structure, exceeded the PEL value suggests a relationship between storing boxes of broken lamps inside the containment structure and elevated mercury concentrations.

The Jerome analyzer was used to measure mercury concentrations when the crushing activity had ceased and when boxes of broken bulbs were present inside the containment structure (*refer to Figure 4. 14*).

Figure 4. 14: Jerome Results – Inside Containment, AERC Melbourne Box Test [a]



[a] The TLV is included on the graph as a point of reference. The mercury concentrations shown on this graph represent instantaneous measurements and do not represent eight-hour TWAs.

After an initial spike in mercury concentration to 0.6 mg/m^3, measurements dropped below the PEL and then steadily increased over time. After 30 minutes, all readings were above the PEL. There was a positive correlation (R^2 = 0.7728) between

mercury concentrations and time. These results show that it is highly likely that the boxes containing broken lamps did contribute to increases in mercury concentrations within the containment structure.

4.6.2 AERC Ashland Box Test

For each device, after conducting EFT #3, two new air sampling pumps were set up in the containment structure. Boxes containing broken bulbs were placed in the containment structure, but no crushing activities were performed. One analytical air sample was collected on the east side of the containment structure, next to the boxes, and one was collected on the west side of the containment structure, away from the boxes. Samples were collected for 36 – 64 minutes (*refer to Appendix A, Table 1 for sample durations*). Table 4. 17 contains the air sampling results for the box test conducted at AERC Ashland.

Table 4. 17: Results for AERC Ashland Box Test

Device	East Side of Containment (Next to Boxes)	West Side of Containment (Away from Boxes)	Sample Duration (min)
Manufacturer A	0.018 mg/m^3	0.10 mg/m^3	64
Manufacturer B	0.12 mg/m^3	0.12 mg/m^3	36
Manufacturer C	0.050 mg/m^3	0.014 mg/m^3	45

While three of the six samples met or exceeded the OSHA PEL, there was no correlation between sample location (proximity to boxes with broken lamps) and mercury concentration. The Jerome analyzer was used at the same time as the analytical air samples, but the readings are not available due to data logger failure. No manual Jerome readings were taken because there was not anyone in the containment structure during the box tests.

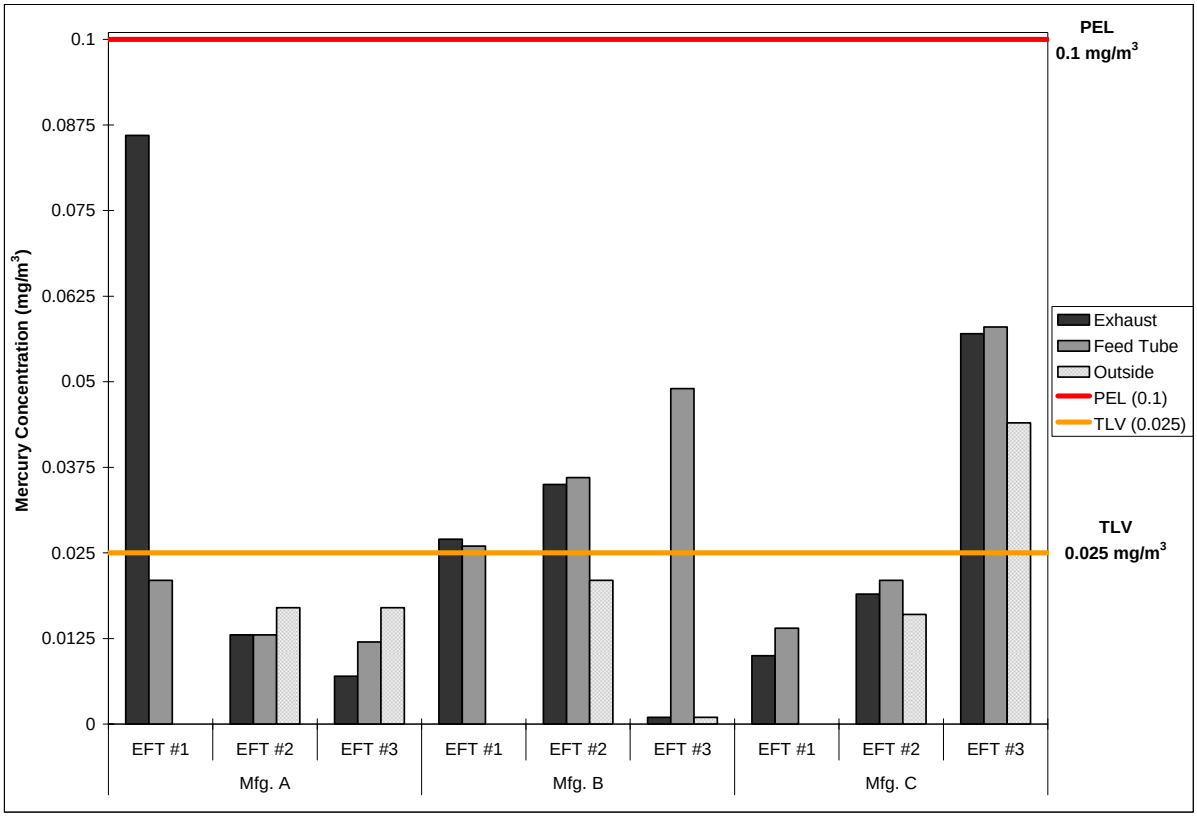
The results from the AERC Ashland box test do not suggest that the broken bulbs in the boxes contribute to elevated mercury concentrations because there was no relationship between the concentration of mercury in the air and the proximity of the air sampling pump to the boxes of broken lamps. However, direct-reading data are not available, so it is not possible to determine whether or not the trend of increasing mercury concentrations in the containment structure over time that was observed in the AERC Melbourne box test is truly representative of what would happen in such a scenario (i.e., boxes containing broken bulbs being stored in a confined space). Therefore, this is an area where future research may be appropriate.

4.7 Overnight Samples

In order to ascertain whether measurable amounts of mercury escaped from the DTC devices during non-operational periods when the devices were assembled on the top of a drum full of crushed lamps, analytical air samples were collected overnight after the operation of each DTC device. The Manufacturer A device blower was kept running (per the manufacturer's instructions) during the overnight test. In accordance with the manufacturers' instructions, the power to the Manufacturer B

and Manufacturer C devices were shut down when the devices were not in use. The results of the overnight tests are presented in Figure 4. 15.

Figure 4. 15: Overnight Test Sample Results



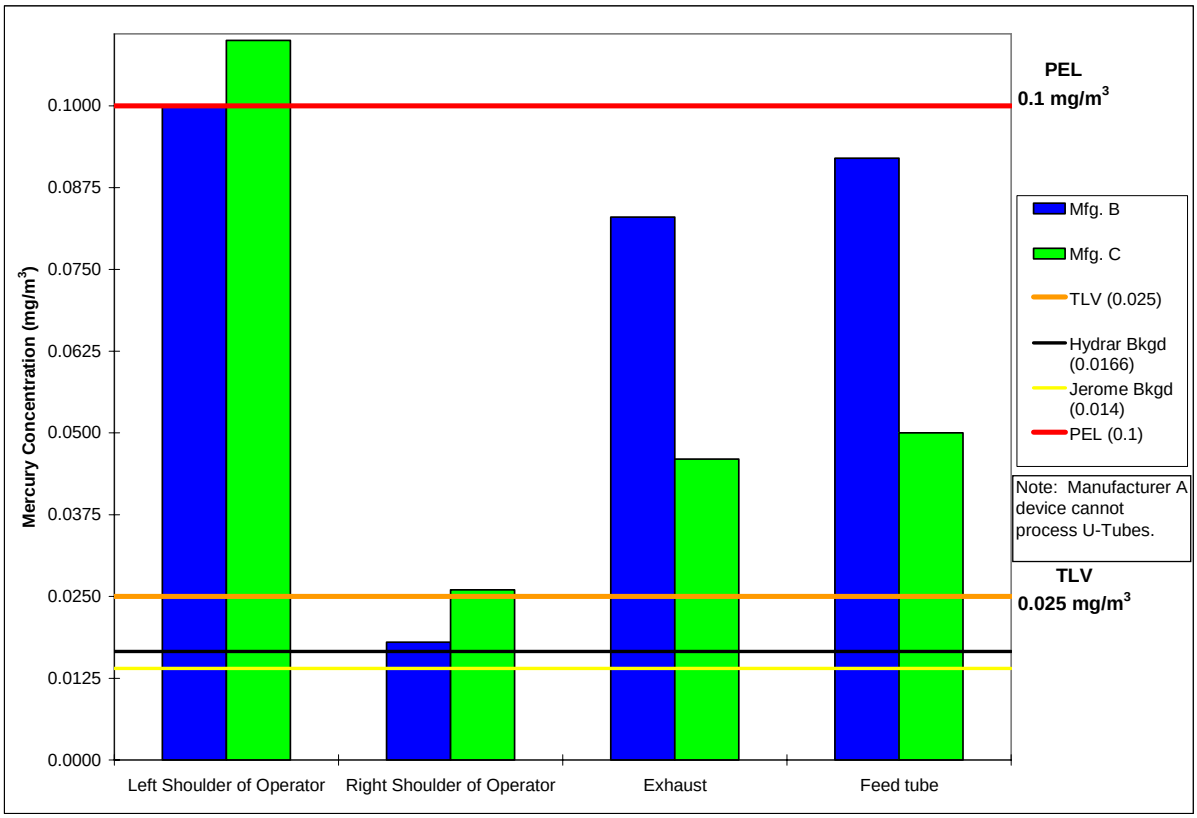
Because overnight samples were collected to assess general release during non-operational periods, values should not be compared to the OSHA PEL or the ACGIH TLV, which is a standard for worker exposure during a regular work day. The lines for the PEL and the TLV are included on the graph as points of reference. The overnight sampling was inconclusive as to whether idle DTC devices attached to partially filled drums of lamps leaked mercury vapors. The concentrations measured overnight were variable. In EFT #1, the overnight sample collected for the Manufacturer A device near the exhaust was much higher than any of the other samples. This may somehow relate to the fact that the Manufacturer A device was the only device that was left on overnight, per instructions in the operations manual.

In EFT #2 and EFT #3, air samples were collected outside the containment structure, as well as inside the containment structure. The overnight samples collected in the containment structure after operating the Manufacturer A device were below the values measured outside the containment structure. Three of the four overnight samples collected inside the containment structure after crushing lamps for the Manufacturer B device measured above the levels measured outside the containment structure. All four of the overnight samples collected inside the containment structure during EFT #2 and EFT #3 for the Manufacturer C device were higher than the outside samples.

4.8 U-Tube Test

The Manufacturer B and Manufacturer C devices have attachments that enable them to process "U" tube lamps (U-tubes). As discussed in Section 3.1.4.2, at the end of EFT #3 at AERC Ashland, a test was conducted to evaluate the airborne mercury levels from the two devices while processing U-tubes. The intent was for both the Manufacturer B and Manufacturer C devices to process enough U-tubes to fill a 55-gallon drum. However, the facility was only able to collect a limited number of U-tubes for the U-tube study, so the available U-tubes were divided between the two devices. The Manufacturer B device processed a total of 85 U-tubes, and the Manufacturer C device processed a total of 89 U-tubes. The sampling duration was 12 minutes for the Manufacturer B device and 14 minutes for the Manufacturer C device. The U-tube air sampling results are presented in Appendix A, Table 1 and shown in Figure 4. 16.

Figure 4. 16: U-tube Test Sample Results[a]



[a] The TLV is included on the graph as a point of reference. The analytical air samples shown on this graph do not represent eight-hour TWAs (*refer to Appendix A, Table 1 for sample durations*).

All samples, except for the Manufacturer B sample on the operator's right shoulder, were above the TLV value. Furthermore, two of the operator breathing zone samples (one for the Manufacturer B device and one for the Manufacturer C device) equaled or slightly exceeded the PEL value. These levels are generally higher than the results from processing the straight lamps, especially in light of the fact that so few U-tubes were processed by each device. A possible explanation for the high mercury levels is the fact that the opening for the U-tube attachment was much larger than the opening for the feed tube for the straight lamps.

5. MASS BALANCE STUDY

The goal of the Mass Balance Study was to estimate for each DTC device its effectiveness in capturing and retaining mercury in the device, expressed as a percent of the total mass of mercury fed into the DTC device. A successful Mass Balance Study would also allow assessment of the total mercury released to the environment due to DTC use, and also to support assessment of potential secondary exposures to mercury from lamp crushing. For each DTC device, the total mercury contained in enough lamps to fill one drum was estimated, and this quantity was then compared with the total mercury detected in samples collected during PVS – Phase I, including: crushed lamps from the drum, DTC pollution control media (particulate, HEPA, and carbon filters), and analytical air samples. See Section 5.1 for the mathematical mass balance equation.

The following sections describe the methodology for, and present the results of, the Mass Balance Study. Note that these results represent the best achievable efforts based on the techniques, methods, equipment, and conditions tested. In some cases (e.g., estimating the quantities of mercury in the unprocessed lamps), there are no agency-approved test methods; therefore, it was necessary to rely on either the manufacturer's internal testing results (i.e., QC testing) or on the results from the methods improvised by the project laboratory, which were intended to simulate the manufacturer's test apparatus. The objectives of this project were strictly research and investigation, and the data generated may or may not be suitable for other purposes, such as human health risk assessment.

5.1 Mass Balance Equation

The mass balance mathematical equation is:

$$Hg_T = Hg_C + Hg_R \qquad \textbf{Equation 5. 1}$$

where: Hg_T is the estimated total mercury content of unprocessed lamps
Hg_C is mercury captured in the DTC device (specifically within the air filter media or "filters" and crushed lamps)
Hg_R is mercury released to the ambient air from the DTC device

Hg_T is determined by the average quantity of mercury in a typical fluorescent lamp, multiplied by the number of lamps processed in the DTC device *(refer to Section 5.2)*. Hg_C is determined by the quantity of mercury measured in the crushed lamps and in the various filters *(refer to Section 5.3)*. Hg_R is determined by the quantity of mercury measured in the ambient air within the containment structure, as determined by area and personnel air samples *(refer to Section 5.4)*.

5.2 Estimating Total Mercury Content of Unprocessed Lamps (Hg_T)

As mentioned above, the first important step in the Mass Balance Study was to estimate the input mercury, or the quantity of mercury contained in a typical set (i.e., one drum's worth) of unprocessed lamps. In theory, this amount should be 100 percent of the total mercury available for potential release to the crushed lamps, the

air filtration system, and as fugitive emissions to the surrounding indoor air. Any difference between this amount and the total of the component terms on the right-hand side of Equation 5.1 thus is a measurement of the potential error in this study.

Philips Lighting (Philips) "Alto®" fluorescent lamps (also referred to as "green tip" lamps) were used during this part of the DTC Study. According to e-mail correspondence from Mr. Steve McGuire of Philips to Mr. Tad Radzinski of EPA, these lamps are manufactured to achieve a specific mass content of mercury, depending on the type of lamp (Table 5. 1), and the tolerance on the mercury content is +/- 0.1 mg of mercury. The mercury content is determined using a test procedure and testing apparatus that Philips has developed specifically for this purpose. Energized (lighted) mercury lamps are attached to the testing apparatus and then chilled using dry ice or other super-cooled vapor. The cooling process condenses the mercury vapor, eventually causing the light to be extinguished. After cooling, a hole is drilled in the metal end cap of the lamp, and an acid extraction method is used via the hole in the metal end cap to recover the mercury for quantitative analysis (*refer to Appendix E*).

Table 5. 1: Mass of Mercury in Philips Lighting Alto® Fluorescent Lamps

Type of Lamp	Mass of Mercury Per Lamp (mg)	Manufacturer's Tolerance (mg)
T-8	3.5	+/- 0.1
T-12 (34 Watt)	4.4	+/- 0.1
T-12 (39 Watt)	3.5	+/- 0.1
T-12 (40 Watt)	4.4	+/- 0.1

In order to approximate real-world operating conditions for the DTC Device Study, spent lamps were processed. To obtain data regarding the mercury content of the spent lamps, a sample of unbroken, Alto® lamps were removed from the stockpile and submitted to Data Chem for analysis of total mercury. These results are contained in Table 5. 2. The data are generally lower than the results provided by Philips for new lamps. This difference is possibly due to small leaks of mercury that occurred during the operating lives of the lamps. Other factors, such as reaction of mercury vapor with lamp components leading to conversion of elemental mercury into salts, dissolution of the mercury into the lamp glass, or binding of mercury to other lamp components, might contribute to this disparity but were not a subject of this study. (The reaction of mercury vapor with lamp components was studied by Hildenbrand, et al.[26] and Jang, et al. [27])

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[26] *Refer to Hildenbrand, V. D.; Denissen, C. J. M.; Geerdinck, L. M.; van der Marel, C.; Snijders, J. H. M.; and Tamminga, Y. 2000. Interactions of thin oxide films with low-pressure mercury discharge. Thin Solid Films. 371: 295-302.*

[27] *Refer to Jang, Min; Hong, Seung Mo; and Park, Jae K. 2005. Characterization of recovery of mercury from spent fluorescent lamps. Waste Management. 25: 5-14.*

Table 5. 2: Total Mercury in Spent Philips Lighting Alto® Fluorescent Lamps [a]

Type of Lamp	Fluorescent Lamp Mercury Quantity (mg)	Mean Mercury Quantity (mg)	Standard Deviation
T-8	3.0	3.0 (10 – 15 mg/kg)	0.082
	2.9		
	3.1		
T-12 (34 Watt)	4.2	4.2 (14 – 21 mg/kg)	0.12
	4.4		
	4.1		
T-12 (40 Watt)	4.3	3.6 (12 – 18 mg/kg)	0.75
	2.8		

[a] No samples of T-12 39 Watt lamps were available for this analysis.

The total mass of mercury in the lamps processed in each DTC device was estimated using the total number of each type of lamp processed and the mean mercury content of each lamp, as shown in Equation 5.2.

$$Hg_T = N_L * Hg_L \qquad \textbf{Equation 5. 2}$$

where: Hg_T is the estimated total mercury content of unprocessed lamps
N_L is the total number of lamps processed
Hg_L is the mean mercury content of a single lamp

Means for mercury content for each lamp type were determined from either the unbroken lamp samples collected during the study or the information provided by Philips Lighting. In general, use of the study sampling results was preferred, except in the case of the T-12 39 Watt lamp type, where no data were available (*see footnote to Table 5. 2*). The rationale for using the study data over the manufacturer's averages was that the unbroken lamps were obtained from the broader collection of actual used lamps arriving at the respective facilities and thus were believed to be more representative for this study.

After the conclusion of the DTC Study, research was published regarding the efficacy of acid extraction of mercury from fluorescent bulbs (*refer to footnote 27 is Section 5.2*). This issue is discussed further in Sections 5.6 and 5.7.

Table 5. 3 provides an inventory of the types of lamps processed by each device and the estimated total mass of mercury processed through each device during the Mass Balance Study (Hg_T).

Table 5. 3: Mass of Mercury Processed for Each DTC (Hg_T)

Device	Lamp Type	Number of Lamps	Amount of Mercury per Lamp (mg/lamp)	Total Quantity of Mercury (mg)
Manufacturer A	T-12 (34 Watt)	637	4.2	2,675
Total – Hg_T				**2,675 mg**
Manufacturer B	T-12 (34 Watt)	113	4.2	475
	T-8	611	3.0	1,833
Total – Hg_T				**2,308 mg**
Manufacturer C	T-12 (34 Watt)	621	4.2	2,608
	T-12 (39 Watt)	49	3.5	172
	T-12 (40 Watt)	36	3.6	130g
Total – Hg_T				**2,910 mg**

5.3 Estimating Mercury Mass Captured in the DTC Devices (Hg_C)

Mercury was captured inside the DTC devices in either one of two ways:

- Contained within the crushed lamps collected inside the 55-gallon drum beneath the device; or
- Retained as particulate or vapor air emissions retained within the air filtration system that was supplied with the particular device (listed in Table 5. 4).

Section 3.3 provides details regarding the collection of bulk samples, including crushed lamps and pollution control media, for each device. Table 5. 4 summarizes the number and type of bulk samples.

Table 5. 4: Samples Collected for the Mass Balance Study

Manufacturer A Device	Manufacturer B Device	Manufacturer C Device
Crushed lamps – 3 samples	Crushed lamps – 3 samples	Crushed lamps – 3 samples
Top carbon canister – 3 samples	Pre-filter – 1 sample	Pre-filter – 3 samples
Middle carbon canister – 3 samples	Carbon canister – 3 samples	Carbon canister – 3 samples
HEPA filter – 3 samples		HEPA filter – 1 samples

The analytical results for the samples collected for Manufacturer A, Manufacturer B, and Manufacturer C devices are provided in Table 5. 5. Samples from the Manufacturer D device are not presented below because the Manufacturer D device was removed from the Study (*refer to Section 3.5.1*).[28]

[28] During the Mass Balance Study, when only "low mercury" lamps were used and outdoor temperatures were low, operation of the Manufacturer D device resulted in ambient mercury concentrations nearly 9 times the OSHA PEL, highlighting the problems inherent in the use of a poorly designed DTC device.

Table 5. 5: Mass Balance Study Sample Results

DTC Device	Sample Material	Result (w/w)[a]	Result (w/a)[b]	Mean Result	Std. Dev.
Manufacturer A	Crushed Lamps	5.84 µg/g	NA	3.70 µg/g	1.852
Manufacturer A	Crushed Lamps	2.70 µg/g	NA		
Manufacturer A	Crushed Lamps	2.57 µg/g	NA		
Manufacturer A	Carbon Canister (top)	84 µg/g	NA	62 µg/g	25.534
Manufacturer A	Carbon Canister (top)	34 µg/g	NA		
Manufacturer A	Carbon Canister (top)	68 µg/g	NA		
Manufacturer A	Carbon Canister (middle)	39 µg/g	NA	15 µg/g	20.649
Manufacturer A	Carbon Canister (middle)	5.0 µg/g	NA		
Manufacturer A	Carbon Canister (middle)	1.7 µg/g	NA		
Manufacturer A	HEPA Filter	NA	4.2 µg/100 cm^2	5.5 µg/100cm^2	1.253
Manufacturer A	HEPA Filter	NA	6.7 µg/100cm^2		
Manufacturer A	HEPA Filter	NA	5.6 µg/100cm^2		
Manufacturer B	Crushed Lamps	5.17 µg/g	NA	5.11 µg/g	0.4880
Manufacturer B	Crushed Lamps	4.59 µg/g	NA		
Manufacturer B	Crushed Lamps	5.56 µg/g	NA		
Manufacturer B	Pre-Filter [c]	490 µg/g	NA	490 µg/g	N/A
Manufacturer B	Carbon Canister	11 µg/g	NA	22 µg/g	12.220
Manufacturer B	Carbon Canister	19 µg/g	NA		
Manufacturer B	Carbon Canister	35 µg/g	NA		
Manufacturer C	Crushed Lamps	6.07 µg/g	NA	4.69 µg/g	1.975
Manufacturer C	Crushed Lamps	5.58 µg/g	NA		
Manufacturer C	Crushed Lamps	2.43 µg/g	NA		
Manufacturer C	Pre-Filter [c]	180 µg/g	NA	180 µg/g	0.0
Manufacturer C	Pre-Filter [c]	180 µg/g	NA		
Manufacturer C	Pre-Filter [c]	180 µg/g	NA		
Manufacturer C	Carbon Canister	2.7 µg/g	NA	5.8 µg/g	3.053
Manufacturer C	Carbon Canister	6.0 µg/g	NA		
Manufacturer C	Carbon Canister	8.8 µg/g	NA		
Manufacturer C	HEPA Filter	NA	2.3 µg/100 cm^2	2.3 µg/100 cm^2	N/A

[a] Result w/w column of the Bulk Sample Results table is a proportion of weight per weight.
[b] Result w/a column of the Bulk Sample Results table is a proportion of weight per area.
[c] "Pre-filter" primarily consisted of phosphor with a few glass fines. The pre-filter was collected off a paper sock filter (Manufacturer B device) or a vacuum-bag type filter (Manufacturer C device).
NA – Not applicable
µg/g – micrograms per gram
µg/100 cm^2 – micrograms per 100 square centimeters

The device manufacturers were instructed to submit clean filter media to Data Chem for quality control (QC) samples. These clean materials were used for laboratory blanks and matrix spikes. The blank sample values are shown in Table 5. 6. The spike values and recoveries are listed in Table 5. 11 and discussed in Section 5.6.2. Table 5. 6 also presents the weight or area information for the samples, as applicable. Results are reported as either a mass of mercury per weight or a mass of mercury per area. The methods used to measure the weight of the samples are described in Section 3.3. The manufacturers provided the nominal areas of each type of filter used in the various devices. Prior to performing the mass balance calculations, all values were converted from standard units (i.e., pounds [lb] or square inches [in^2]) to metric units (i.e., grams [g] or square centimeters [cm^2]). Table 5. 7 presents the measured mass of mercury captured in each of the different media (i.e., [mean concentration]*[applicable weight or area]), in milligrams (mg).

Table 5. 6: Total Weights, Areas, and Blank Mercury Concentrations of Bulk Sample Media

Device	Weight of Crushed Lamps		Weight of Pre-Filter		Area of HEPA Filter Media		HEPA Filter Blank (µg/sample)		Weight of Carbon Canister		Carbon Canister Blank (µg/g)	
	lb[(a)]	g	lb[(a)]	g	in^2[(a)]	cm^2			lb[(a)]	g		
Manufacturer A	466	211,374	NA	NA	7,632	49,239	ND	ND	29/bag	13,154	7.4	20.0
Manufacturer B	331	150,139	0.056	25.4	NA	NA	NA	NA	0.742	337	ND	ND
Manufacturer C	436	197,766	0.58	263	194	1,250	ND	ND	22	9,979	ND	ND

[a] Actual measured weight or area of the media.
NA – Not applicable
ND – Not detected

Table 5. 7: Estimated Mercury Mass Captured inside DTC Devices (Hg_C)

Device	Sample Type	Concentration	Weight or Area	Total Hg (mg)
Manufacturer A	Crushed Lamps	3.70 µg/g	211,374 g	782
	HEPA Filter	5.5 µg/100 cm^2	49,239 cm^2	2.7
	Carbon Canister (top)	62 µg/g	13,154 g	816
	Carbon Canister (middle)	15 µg/g	13,154 g	197
Total – Hg_T				**1,798**
Manufacturer B	Crushed Lamps	5.11 µg/g	150,139 g	767
	Pre-Filter	490 µg/g	25.4 g	12
	Carbon Canister	22 µg/g	337 g	7.4
Total – Hg_T				**786**
Manufacturer C	Crushed Lamps	4.69 µg/g	197,766 g	928
	Pre-Filter	180 µg/g	263 g	47.3
	HEPA Filter	2.3 µg/100 cm^2	1,250 cm^2	0.029
	Carbon Canister	5.8 µg/g	9,979 g	58
Total – Hg_T				**1,033**

5.4 Estimated Mercury Released To The Ambient Air (Hg_R)

The total mass of mercury released to the ambient air from each DTC device (Hg_R) was estimated using the air sampling data collected during PVS – Phase I. The method for calculating Hg_R is shown in Equation 5.3.

$$Hg_R = N_{AE} * [Hg] * V \qquad \textbf{Equation 5. 3}$$

where: Hg_R is mercury released to the ambient air from the DTC device
N_{AE} is the estimated number of air exchanges
[Hg] mean air concentration in containment structure during PVS I
V is the volume of the containment structure

The mean of the four area air sample results (two samples at the feed tube and two samples at the device exhaust) was calculated for each DTC device. The containment structure measured 12 feet by 12 feet by 10 feet, for a volume of 1,440 cubic feet (ft^3), which converts to 40.78 cubic meters (m^3).

During the operation of all devices, movement in and out of the containment structure was limited to supplying boxes of lamps to the operator and the industrial hygienist collecting the air samples, thus limiting (to the extent practicable) the exchange of air between the containment volume and the outside. In addition, as described previously in Section 2.2, the construction of the containment space itself (e.g., taped and overlapping plastic sheeting) aided in isolating the space and limiting air movement. While the number of air exchanges was not specifically measured, it was estimated using Equation 5.4.

$$N_{AE} = (Q * t) / V \qquad \textbf{Equation 5. 4}$$

where: N_{AE} is the estimated number of air exchanges
Q is the volumetric flow rate of air coming out of the device exhaust
t is the duration of the area air sampling
V is the volume of the containment structure

Table 5. 8 presents the mean mercury concentrations in the air samples and the estimated mass of mercury released (Hg_R) for each device:

Table 5. 8: Mercury Released from DTC Devices (Hg_R)

Device	Flow Rate (ft^3/min)	Time (min)	Number of Air Exchanges	Mean Mercury Concentration (mg/m^3)	Volume (m^3)	Mercury Released (Hg_R)
Manufacturer A	25 [a]	112	1.9	0.0094	40.78	0.75 mg
Manufacturer B	34 [b]	86	2.0	0.010	40.78	0.82 mg
Manufacturer C	42 [b]	100	2.9	0.0095	40.78	1.3 mg

[a] Estimate from owner's manual.
[b] Measured during operation.

While the reported values for the number of air exchanges are estimates, they do not significantly affect the mass balance because $Hg_R << Hg_C$ (refer to Table 5. 9).

Originally, it was also intended to include the wipe sampling results from the interior surfaces of the polyethylene containment structure, to attempt to quantify the contribution of mercury vapor condensation to the overall mass balance. However, this process was impacted by the unexpectedly high ambient concentrations of mercury inside the facilities. Due to these high ambient concentrations, it would not have been possible to effectively differentiate mercury vapors released by the device and condensing on the polyethylene sheeting from vapors already existing in the air and condensing on the sheeting. Furthermore, some of the mercury mass might have been double-counted under such a scenario. Therefore, wipe sampling results were excluded from the Mass Balance Study. Refer to Appendix F for a discussion of the wipe sample results.

5.5 Mass Balance Results

Sections 5.2, 5.3, and 5.4 described the methods used to derive the mass of mercury that was used in the mass balance calculations. Table 5. 9 is a summary of the total mass of mercury contributed by each source.

Table 5. 9: Summary of Mercury Mass Contributions, By Source

Device	Hg_C					Hg_R
	Crushed Lamps	Pre-Filter	HEPA Filter	Carbon Canister(s)	Total	
Manufacturer A	782 mg	NA	2.7 mg	1,013 mg [a]	1797.7 mg	0.75 mg
Manufacturer B	767 mg	12 mg	NA	7.4 mg	786.4 mg	0.82 mg
Manufacturer C	928 mg	47.3 mg	0.029 mg	58 mg	1033.329 mg	1.3 mg

[a] Combined recovery by the top and middle carbon canisters on the Manufacturer A device.

Table 5. 10 contains the results of the mercury mass balance calculation for each device, as well as the percentage of mercury accounted for compared to the estimated mass of mercury processed (i.e., the mercury content of the unprocessed whole lamps).

Table 5. 10: Mass Balance Calculation Results

Device	Hg Processed (Hg_T)	Hg Recovered ($Hg_C + Hg_R$)	% Recovery
Manufacturer A	2,675 mg	1,798 mg	67.3 %
Manufacturer B	2,308 mg	787 mg	34.1 %
Manufacturer C	2,910 mg	1,035 mg	35.6 %

5.6 Mass Balance Discussion

Based on the mass balance results obtained from this study and presented in Table 5. 10, the total mercury mass accounted for (Hg_C + Hg_R) was about one third to two thirds less than the estimated input of mercury (Hg_T). Several variables may have contributed to the inability to account for a fairly large percentage of the mercury. Three of the most likely variables that would affect the mass balance are: 1) inaccuracies in the determination of mercury in the crushed lamps; 2) inaccuracies in the determination of mercury in the filter media due to poor recovery during the laboratory analysis; and 3) absorption of mercury on polyethylene (the containment structure) and inside the DTC device. In addition, there is no approved laboratory procedure to estimate the mercury content of whole fluorescent lamps, making this factor another possible cause of the imbalances noted during this study.

5.6.1 Mercury Mass in Crushed Lamps

As indicated by the results summarized in Table 5. 9, a substantial fraction of the mercury produced during the crushing of lamps in the DTC devices accumulates in the crushed lamps. Therefore, this variable has a substantial influence on the mass balance results. It was closely studied to attempt to understand the reason for the disparity between the total mercury mass in the lamps before processing and the mercury mass accounted for after processing.

The proportion of the total mercury mass detected (Hg_C + Hg_R) in the crushed lamps was 43 percent for the Manufacturer A device, 97 percent for the Manufacturer B device, and 90 percent for the Manufacturer C device. The lower percentage observed for the Manufacturer A device can be attributed to the relatively larger capture of mercury mass in the more extensive air filtration equipment (HEPA filter and carbon filters) associated with this device. As can be noted from Table 5. 9, the actual mercury mass in the crushed lamps from each of the three devices are similar (having the same orders of magnitude).

The sample results for the crushed lamps for all devices in general may have been biased low, for three reasons.

- The method of collecting the samples of crushed lamps involved digging as deep into the drum as possible to collect the samples. However, due to the high density of the crushed lamps (caused by the unaided compaction of the crushed glass and other debris), the samples could only be collected at a depth of approximately eight inches. The operation of each DTC device causes the drum to vibrate, and this vibration may have caused the phosphor powder fraction of the crushed lamps to stratify vertically within the drum. An analysis of the crushed lamps components indicates that the majority of the mercury will be condensed onto this fine phosphor powder *(refer to Appendix G)*, thus causing an unequal distribution of mercury mass with lower concentrations on top. Jang, et

al. (2005) [29] and Raposo, et al. (2003)[30] provide further information on the distribution of mercury in spent fluorescent lamps. Because of this likely distribution of phosphor powder in the drum, samples collected at a depth of eight inches would likely not be representative of the contents of the drum.

- Some mercury likely volatized and was released during the collection of the crushed lamps samples from the drum, compositing the samples, and transfer of the material to the sample containers.

- Additional handling and sorting of the composite samples at the laboratory may have resulted in further volatilization of mercury.

Due to a miscommunication between Booz Allen Hamilton and Data Chem, the laboratory initially analyzed only the phosphor powder and glass fines portion of the crushed lamps bulk samples. The results for the mercury concentration in crushed lamps that were obtained in this first analysis were greater than the mercury concentrations in unbroken lamps by an order of magnitude.

When this error was identified, the laboratory was instructed to analyze the remaining crushed lamp sample material (i.e., the broken glass and lamp end caps). The combined results from both analyses were used to estimate mass of mercury in the crushed lamps for the mass balance. Appendix G presents a discussion of the two sets of results.

5.6.2 Mercury Mass in Air Filtration System Elements

An important variable in the mass balance equation is the analytical results for mercury in the various air filtration media associated with the DTC devices. As discussed below, the laboratory-reported concentrations of mercury from the carbon media and the HEPA filters contained significant errors. Because the pre-filters were easily accessible and the amount of material collected in the pre-filters was limited, the pre-filter sampling data are likely to be accurate, and thus, the efforts to identify probable sources of error focused on the HEPA filters and the activated carbon.

Laboratory spike samples were prepared and analyzed, to assess potential matrix interferences from the filter or carbon media, as applicable. Manufacturer A, Manufacturer B, and Manufacturer C were contacted and instructed to submit clean filter media samples to Data Chem. Manufacturer A and Manufacturer C each submitted a HEPA filter and carbon canister, and Manufacturer B submitted its composite filtration cartridge, which consists of a particulate/pre-filter and a carbon canister. The quantity of mercury with which to spike each media was based on the results obtained during prior DTC device tests in this study. Data Chem prepared and analyzed four spike samples and two blank samples per media.

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[29] *Refer to Jang, Min; Hong, Seung Mo; and Park, Jae K. 2005. Characterization of recovery of mercury from spent fluorescent lamps. Waste Management. 25: 5-14.*

[30] *Refer to Raposo, Cláudio; Windomöller, Cláudio Carvalhinho; and Júnior, Walter Alves Durão. 2003. Mercury speciation in fluorescent lamps by thermal release analysis. Waste Management. 23: 879-886.*

The results for these QA/QC samples are given in Table 5. 11.

Table 5. 11: Spike and Blank Analytical Results for Pollution Control Media

Device	Media	Spiked Concentration	Recovered Concentration	Percent Recovery
Manufacturer A	Carbon (C1)	60 µg/g	67 µg/g	112%
Manufacturer A	Carbon (C2)	60 µg/g	56 µg/g	93%
Manufacturer A	Carbon (C3)	60 µg/g	60 µg/g	100%
Manufacturer A	Carbon (C4)	60 µg/g	100 µg/g	167%
Manufacturer A	Carbon Blank (CB1)	0 µg/g	7.4 µg/g	NA
Manufacturer A	Carbon Blank (CB2)	0 µg/g	20 µg/g	NA
Manufacturer A	HEPA Filter (F1)	2 µg/sample	2.2 µg/sample	110%
Manufacturer A	HEPA Filter (F2)	2 µg/sample	2.1 µg/sample	105%
Manufacturer A	HEPA Filter (F3)	2 µg/sample	2.2 µg/sample	110%
Manufacturer A	HEPA Filter (F4)	2 µg/sample	2.2 µg/sample	110%
Manufacturer A	HEPA Filter Blank (FB1)	0 µg/g	ND	NA
Manufacturer A	HEPA Filter Blank (FB2)	0 µg/g	ND	NA
Manufacturer B	Carbon (C1)	20 µg/g	4.5 µg/g	23%
Manufacturer B	Carbon (C2)	20 µg/g	4.4 µg/g	22%
Manufacturer B	Carbon (C3)	20 µg/g	4.3 µg/g	22%
Manufacturer B	Carbon (C4)	20 µg/g	4.3 µg/g	22%
Manufacturer B	Carbon Blank (CB1)	0 µg/g	ND	NA
Manufacturer B	Carbon Blank (CB2)	0 µg/g	ND	NA
Manufacturer C	Carbon (C1)	6 µg/g	3.4 µg/g	57%
Manufacturer C	Carbon (C2)	6 µg/g	3.6 µg/g	60%
Manufacturer C	Carbon (C3)	6 µg/g	3.6 µg/g	60%
Manufacturer C	Carbon (C4)	6 µg/g	3.6 µg/g	60%
Manufacturer C	Carbon Blank (CB1)	0 µg/g	ND	NA
Manufacturer C	Carbon Blank (CB2)	0 µg/g	ND	NA
Manufacturer C	HEPA Filter (F1)	1 µg/sample	0.67 µg/sample	67%
Manufacturer C	HEPA Filter (F2)	1 µg/sample	0.84 µg/sample	84%
Manufacturer C	HEPA Filter (F3)	1 µg/sample	0.72 µg/sample	72%
Manufacturer C	HEPA Filter (F4)	1 µg/sample	0.76 µg/sample	76%
Manufacturer C	HEPA Filter Blank (FB1)	0 µg/g	ND	NA
Manufacturer C	HEPA Filter Blank (FB2)	0 µg/g	ND	NA

ND – Not detected above the analytical limit of detection.
NA – Not applicable

Differences between the spiked concentration and detected concentration generally reflect potential interferences caused by the pollution control media, as well as

analytical error. As indicated above, the Manufacturer B carbon media, Manufacturer C carbon media, and Manufacturer C HEPA filter produced results with very low recoveries. Thus, portions of the mercury that are not accounted for in the mass balance could have been retained in the pollution control media for these two devices but may not have been detected in the laboratory analysis. The Manufacturer A carbon media spikes generally produced results above 100 percent, which is consistent with the mercury detected in the manufacturer-supplied blanks. The HEPA filter spikes were also slightly above 100 percent in all cases, but are within $\pm$ 10 percent of the actual spiked value. No mercury was detected in the HEPA filter blanks.

5.6.3 Mercury Mass Adhering to Surfaces

Difficulties with contamination prevented the use of the wipe samples collected for the mass balance. Bulk samples of the polyethylene used for each containment structure were not collected. Because mercury permeates through and adheres to polyethylene, a significant portion of the mercury not accounted for in the mass balance may have been associated with the containment structure. It is also possible that some amount of mercury adhered to the insides of the DTC devices.

5.6.4 Mercury Mass in Ambient Air

The mass of mercury released during DTC device operation (Hg_R) was calculated based on Equation 5.3, which included the number of air exchanges, the concentration of mercury in the air inside the containment structure, and the volume of the containment structure. The number of air exchanges was not measured during the Study; numbers of air exchanges were calculated for each device based on the speeds of the exhaust fans. However, the errors associated with these numbers are not known, and these errors would affect the result of the Hg_R calculation. Additionally, it is possible that some portion of the mercury released from the DTC devices permeated through the containment structure and, therefore, was not accounted for in the mass balance equation.

5.7 Mass Balance Study Observations

A Mass Balance Study was conducted in order to determine whether the mercury from lamps crushed in the various DTC devices could be accounted for in recognizable mass flows associated with operation of the devices (i.e., crushed lamps, air filtration equipment, and fugitive emissions to the air). The study was unable to establish a concrete relationship between mass input and output, based on the media and waste streams that could be readily sampled during these tests. For all three devices, the estimated input mercury quantities on a mass basis were substantially larger than the measured output quantities. The following factors should be considered in designing any future Mass Balance Study.

- Appropriate sampling procedures for the crushed lamp samples need to be developed. The drum used for sampling the crushed lamps could be retrofitted to allow multiple samples to be collected at various depths within the drum.

- Any steps taken to avoid releases to the air when creating a composite sample and expediting transfer of the sample to the container will likely reduce mercury losses.

- A validated and approved test method for quantifying the mercury in whole unbroken lamps is needed, including an understanding of the relative accuracy and error inherent to such a test.

- An approved test method for quantifying the mercury in the pollution control media (HEPA, carbon, and particle filters) is needed, including an understanding of the relative accuracy and error inherent to such a test.

- The material used to construct the containment structure could have a significant affect on the containment and measurement of mercury. A material better suited to mercury sampling, such as vinyl, should be considered if a containment structure is used.

- Wipe sampling procedures need to be improved and pre and post samples of the material used to construct the containment structure may be necessary.

No scientific methodology was applied to attempt to understand the relative impact of each of the above factors on the results presented here because it was beyond the scope of this Mass Balance Study.

6. LIMITATIONS

After reviewing the data collected during the Study, a number of factors were identified that may have affected the study results:

- Mercury background levels inside the facilities where the tests were performed
- Differences in environmental conditions (i.e., temperature and relative humidity) at each test site resulting in greater or lesser volatilization of mercury
- Cross-contamination from lamps broken during shipment to the processing site
- Contamination from lamps broken during operation.

This section provides a summary of how these factors may have influenced the study results.

6.1 Background Levels of Mercury

The DTC Device Study was conducted at operational lamp recycling facilities that crush large quantities of spent fluorescent lamps. At AERC Ashland and AERC Melbourne, the DTC devices were operated in a separate bay from the primary lamp processing areas. At EPSI Phoenix, due to the configuration of the plant, the tests could not be isolated from the normal plant operations as effectively as at the other sites. The Study was conducted at fluorescent lamp recycling facilities for several reasons:

- These facilities possessed the appropriate permits to process mercury-containing fluorescent lamps.

- These facilities had ample supplies of fluorescent lamps that were provided at no cost to the study team.

- The facilities had the capacity to process and dispose of the drums of crushed lamps, with no shipping, manifesting, or disposal arrangement required of the study team.

The study team made every effort to isolate the study area from normal lamp processing operations. At all three locations, a containment structure of plastic sheeting was constructed around the study area; however, as discussed below, this was only partially effective as a barrier to ambient, background mercury contamination.

At the beginning of testing at each location, two analytical air samples were collected in the immediate vicinity of the study area, to attempt to measure background mercury concentrations inside the lamp recycling facility. The results indicated that each facility had elevated concentrations of mercury in the ambient air. (*Refer to Table 4. 1 and Table 4. 2 for the background concentration measurements for each facility*.)

The background mercury concentration affected, to some extent, the analytical sample results. Elevated background concentrations would have the potential to

bias any study results and may affect the validity of conclusions drawn from the Study by:

- Elevating the ambient air sampling analytical results and real-time (i.e., Jerome) readings above what they would have been if background conditions were not characterized by elevated levels of mercury; and

- Causing deposition of mercury on the containment area surfaces, which later could have re-volatilized during the tests and created "false positives" or led to exceedances of OSHA or ACGIH standards.

The high background mercury made it more difficult to definitively attribute the mercury measurements to the DTC devices. In retrospect, background sampling was likely inadequate to fully characterize this confounding factor. If future research is conducted in an industrial lamp recycling facility, it will be important that rigorous background sampling be performed, which could include collecting analytical air samples and direct-reading air measurements before, during, and after testing.

6.2 Experimental Conditions

As mentioned in Section 4.4.3, the outside temperatures were 25ºF-50ºF higher during Phase II of the PVS (performed in June 2003) than during Phase I (performed in February 2003), which could have elevated the indoor temperature during air volume changes (e.g., doors opening). An increase in ambient temperature has been shown to cause an increase in volatilization of mercury, resulting in greater detected concentrations (*see footnote 22 in Section 4.4.3*). The Study was not designed to account for the change in ambient temperature when comparing the results from PVS – Phase I to the results from PVS – Phase II. As a result, it is difficult to determine the extent to which any differences in measured mercury concentrations were directly caused by a decline in device performance. To make such a determination possible, in conducting future research, the environmental conditions of the test should be maintained at constant levels.

6.3 Contamination from Lamps Broken During Shipment

Another source of potential contamination of mercury during the Study was the shipping boxes containing the fluorescent lamps that were received at the lamp recycling facilities. On average, approximately 10 percent of the lamps in each box were observed to be broken during shipment to, and/or pre-handling in, the lamp recycling facility. In order to investigate this hypothesis, box tests were conducted. The box test results were discussed in Section 4.6.

At AERC Melbourne, measurable ambient concentrations of mercury were recorded in the containment structure, while boxes of broken lamps were present and open, and no lamps were being crushed (*refer to Figure 4. 14*). Many of these concentrations exceeded the PEL and/or TLV values. Measurable concentrations, the majority of which were also above the PEL and/or TLV values, were also noted from ambient air sampling during a follow-up box test conducted at AERC Ashland. The study results

suggest that, to minimize operator exposures, boxes of lamps (especially those with significant breakage) should be staged in a separate area from the DTC device and preferably one where: 1) worker contact is minimal (e.g., a locked storage closet); and 2) workers accessing the area have the necessary PPE, respiratory protection. This information is important for all persons working with or around spent lamps, not just DTC device operators.

6.4 Contamination from Lamps Broken During DTC Device Operation

As will be discussed in Chapter 7, lamps occasionally broke while they were being fed into the DTC devices. The mercury released from these lamps directly relates to operator exposure during DTC device operation. The occurrences of lamp breakage were not consistent throughout the Study, so it is difficult to determine the average impact that lamp breakage during device operation had on the results of the Study.

7. DISCUSSION

Purposely breaking large numbers of mercury-containing fluorescent lamps can release substantial amounts of mercury to the air. Containing the released mercury is the central goal in the design and operation of drum top lamp crushing devices. The basic purpose of this Study was to examine how well the tested DTC devices met the design goal of containing mercury (as measured by operator exposure) when in routine use. The Study examined the performance of four devices over a five month period. Over the course of the Study, approximately 5,500 lamps were crushed by each of the three devices used throughout the Study, inside a constructed enclosure over a range of environmental and operational conditions. A considerable amount of data was generated that provides insight into the performance of DTC devices during field applications.

Testing in this Study was performed under low ventilation conditions, within a constructed containment structure. This was done both to measure ambient mercury concentrations during device operation in a controlled environment (i.e., segregated from the ambient background mercury at the lamp recycling facilities) and to evaluate performance under plausible, worst-case operating conditions (such as in an unventilated truck trailer).[31] Operator exposures would be expected to be lower than found in this Study if a DTC device is operated in a room with higher ventilation rates or if far fewer lamps are crushed over a longer period of time (i.e., 40-80 lamps crushed per day as apposed to 400-800 lamps crushed per hour). The containment structure was only partially effective in isolating the Study operations from the background mercury produced by the lamp recycling activities at the facilities used as testing locations in the Study because mercury is able to permeate through and sorb onto polyethylene, which was the material used to construct the containment (*refer to Chapter 6 for further discussion*). Measurements made before testing and during non-operational periods indicated that elevated background levels, which varied by facility, were present throughout the entire Study.

The following discussion is based on the evaluation of results from the air monitoring and sample data collected during the course of the Study. Observations and experience gained during the operation of these devices provide further important information about the use of DTC devices.

7.1 Summary of Results

Over the course of the Study, a total of 185 analytical air samples were collected during device operation (not including overnight and background air samples). Sixty-five samples (35.1 percent) were below both the ACGIH TLV and the OSHA PEL values. Eighty-four samples (45.4 percent) were equal to or above the TLV but

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[31] *The facilities used to conduct the Study had background mercury levels that were higher than would be expected at a location that was not routinely handling mercury, as discussed in detail in Sections 4.2 and 6.1. Correction of data by subtracting the background levels from the sample results may be an appropriate way to view the data, although doing so would not reduce all the exceedances of the PEL or TLV to below those levels.*

below the PEL value, and thirty-six samples (19.5 percent) were greater than or equal to the PEL value.[32]

7.1.1 Exposures during Routine Crushing Operations

Overall, seven operator shoulder samples (i.e., average mercury concentration in the operator breathing zone air) exceeded the PEL value. Three of these samples were collected while testing the Manufacturer B device, one was collected while testing the Manufacturer C device, and three were collected while testing the Manufacturer D device, which was removed from the Study. It is important to note that the shoulder samples were average measurements, taken over the time period required to crush one or two drums of lamps (typically one to three hours). The Jerome analyzer readings, taken inside the containment structure, show the fact that there were a number of excursions above the PEL during routine crushing operations, even when the analytical air samples were not above the PEL. Refer to Figure 4. 3, Figure 4. 6, Figure 4. 8, Figure 4. 10, and Appendix A for graphs of the Jerome analyzer readings.

All three devices that completed the Study, especially the Manufacturer B and Manufacturer C devices, experienced problems in maintaining operator exposures below the ACGIH recommended TLV of 0.025mg/m^3 within the containment structure during routine lamp processing. The TLV value is a time-weighted average (TWA) calculated over a normal eight hour work day that is considered protective of worker health and safety.[33] Analytical air samples collected in the operator's breathing zone and Jerome analyzer results show that the concentration of mercury inside the containment structure was above the TLV value the majority of the time.

The Manufacturer A device maintained operator shoulder sample concentrations below the mercury TLV value during four of the five rounds of testing; the Manufacturer A device exceeded the TLV during EFT #1, when the feeding tube was not properly connected to the drum-top assembly (*refer to footnote 23 in Section 4.5.1.1*). The Manufacturer B and Manufacturer C devices exceeded the TLV value in at least one operator shoulder sample during four of the five testing occurrences, even when corrected for background mercury levels. The only test in which all operator shoulder samples for all three devices were below the TLV value was PVS – Phase I at AERC Ashland in February 2003; this may have been, in part, due to the fact that the devices were new, the outside temperature was lower, and only low mercury, Alto® lamps (manufactured by Phillips Lighting) were processed.

Exhaust or feed tube air samples (sometimes both) for all three devices also exceeded the TLV value during portions of the Study. The Manufacturer A device had feed tube and exhaust samples that exceeded the TLV value only during EFT #1, most

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[32] *This discussion of the number of data that exceeded the TLV and the PEL does not correct for background. There were not enough background data to reasonably estimate the contribution that background mercury could have made to the measured mercury concentrations.*

[33] *The results obtained in the Study were not normalized to an eight hour workday because DTC device use patterns may vary significantly. In some cases only a dozen lamps may be crushed in a single day. In other cases a device may be used to process thousands of lamps from different sources, so the operator may be using the device forty hours a week or more. Therefore, sample results that are greater than the TLV should not necessarily be interpreted to indicate that use of one of the DTC devices included in the Study would result intime-weighted, operator exposure above the TLV.*

likely, because of a missing gasket on the feed tube (*refer to footnote 23 in Section 4.5.1.1*). All exhaust and feed tube samples for the Manufacturer B device were above the TLV value, except those taken during PVS – Phase I. Six of the 10 exhaust and feed tube samples collected for the Manufacturer C device were above the TLV value. The degrees to which temperature and changes in device performance affected these data are topics for future research.

As discussed in Section 3.5.3, the Manufacturer D device performed poorly, allowing the mercury concentrations inside the containment structure to exceed the OSHA PEL value by nearly 9 fold. This device was removed from the test after two rounds of testing due to its poor performance (*refer to Appendix I*).

7.1.2 Exposures during Routine Drum and Filter Changes

When the drum beneath a DTC device is filled with crushed lamps, the DTC device must be secured to a new drum. This operation involves unsealing the DTC device from the drum, lifting it off the drum, and placing it on a new, empty drum. During this operation, the full drum of crushed lamps is open to the air for some period of time during which mercury vapor is released uncontrolled to the air (in this Study, drum changes lasted approximately two to 10 minutes). Because of mercury's volatility under typical indoor conditions, the drum change operation poses the potential for significant mercury release, particularly while the full drum is open to the air (as illustrated by the results below). Minimizing the time during which the full drum is open to the air will help reduce operator exposure to mercury and mercury releases to the environment.

Two types of samples were collected for all three devices during drum changes: drum change samples and ceiling samples.[34] All of the DTC devices tested exceeded the PEL value at least once during drum changes. PEL value exceedances during drum changes were frequent for the Manufacturer B and Manufacturer C devices. The drum change samples for the Manufacturer A device exceeded the PEL value in only one of the five tests (EFT #2). The Manufacturer A device features a larger particulate filter and a larger amount of activated carbon than the other two devices. The more substantial pollution control equipment could, at least partially, explain the differences between the results for the Manufacturer A device and the results for the other devices.

7.1.3 Exposures Resulting From DTC Device Malfunction

There were two major types of malfunctions that occurred and caused increased mercury release and operator exposure – improper device assembly and feed tube jamming. The Manufacturer A device was not assembled correctly during EFT #1 (*refer to footnote 23 in Section 4.5.1.1*), which caused average ambient mercury concentrations to exceed the PEL in the sample collected near the feed tube, and to reach 0.074 ug/m^3 in one operator shoulder sample. The samples collected for EFT #1 were collected over the course of filling two drums, meaning that the mercury

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[34] *Drum change samples and ceiling samples are described in Section 3.1.*

concentrations as measured by analytical air samples were averages of the concentrations in the air throughout the filling of both drums.

The missing seal was replaced for the second drum, so during the second drum, the mercury concentrations inside the containment were most likely lower because the device was assembled correctly. With average mercury concentrations at 74 percent of the PEL value, it is very likely that the mercury concentrations in the operator's breathing zone exceeded the PEL at some point during the filling of the first drum. (There are no Jerome data available for this time period to verify this because the Jerome was in regeneration mode.) These levels were nearly four times the average concentrations measured for this device in the other portions of the Study, showing a higher rate of mercury release as a result of seal failure/improper assembly.

A common malfunction experienced with all the devices was jamming of the feed tube. The Study was not designed to quantify increased ambient mercury concentrations or increased operator exposure caused by this malfunction. When the lamps jammed in the feed tube, debris from inside the DTC device and the drum occasionally blew back towards the operator, indicating that a fraction of the mercury in the lamp that jammed was not being captured by the DTC device.

The high operator exposures experienced during the use of the Manufacturer D device were likely due to poor design and malfunction. As noted in Section 3.5.3 and Appendix I, Manufacturer D sent two different DTC devices of different design for the first two rounds of testing, and the device for the second round of testing was clearly damaged, with a visible crack in the vacuum pump motor housing. However, during Phase I of the PVS, when the device had no visible damage, only "low mercury," Alto® lamps were crushed, and outdoor temperatures were between 28 and 43 degrees Fahrenheit, operation of the Manufacturer D device resulted in ambient mercury concentration nearly 9 times the OSHA PEL value. This highlights the importance of design and optimal operation.

7.1.4 Changes in DTC Performance over Time

The performance validation study was designed to examine the change in performance over time. The Study included five rounds of testing over a 5-month period, and approximately 5,500 lamps were crushed by each device. The data generated by the Study indicate that one device (from Manufacturer A) maintained its ability to contain the mercury released when lamps were crushed over the duration of the Study, while the other two devices that completed the Study declined in performance over this time frame and use. The Study was not designed to determine the reason for the decline in performance by the Manufacturer B and C devices. However, there are several possibilities, including possible saturation of the carbon filter material and wear and tear on DTC device seals. The changes in performance over time documented in the Study may be evidence of potential difficulties in maintaining optimal performance by DTC devices. Careful attention to inspection and maintenance of the devices may make it possible for operators to detect and repair any worn components before their deterioration could result in mercury exposures.

7.1.5 Overnight Tests

Air samples were also collected within the containment structure, near the devices, during non-operational periods, with the DTC devices attached to drums that were full or partially full of crushed lamps. These tests were conducted overnight at all three locations during the EFTS. Per manufacturer instructions, the Manufacturer A device was left running on ventilation mode throughout the course of the tests (that is, the fan/vacuum pump was running, with air being exhausted through the carbon filter, whenever a drum was attached to the device), and the Manufacturer B and Manufacturer C devices were turned off. The results from the overnight samples were inconclusive as to whether or not mercury was released from DTC devices that were attached to drums containing crushed lamps.

7.1.6 U-Tube Test

The Manufacturer B and Manufacturer C devices have attachments that enable them to process U-tubes. A test was conducted to evaluate airborne mercury levels from the two devices while processing U-tubes. The facility was only able to collect a limited number of U-tubes for this test, so each device processed fewer than 90 U-tubes. Seven of the eight U-tube samples were above the TLV value, and two of the operator breathing zone samples (one for each device) equaled or slightly exceeded the PEL value. These levels are generally higher than the levels measured when crushing straight lamps, especially in light of the fact that so few U-tubes were processed by each device. A possible explanation for the high mercury levels is the fact that the U-tube attachments have larger openings than the feed tubes for the straight lamps, which could have allowed some air to flow from inside the device out into the containment structure.

7.1.7 Exposures Resulting from Lamp Breakage

Another source of mercury release associated with use of DTC devices was breakage of lamps either before they were fed into the device, or as they were being fed in. Studies of lamp breakage inside the containment structure via the Box Test indicated that lamps broken during handling may have had an affect on the sample results. Lamps also sometimes broke and shattered while being fed into the DTC. No testing of the resulting mercury release was attempted, because this breakage occurred sporadically and was a random event. However, during the first test of the Manufacturer B device at the EPSI Phoenix facility (EFT #2), the Jerome analyzer readings demonstrate that the ambient mercury concentration increased inside the containment structure when a bulb was broken.

As shown in Figure 4. 8 and Appendix A, Figure 32, the mercury concentration was 0.033 mg/m^3 before a lamp was broken and increased to 0.169 mg/m^3 four minutes after a lamp was broken. This was an increase of 400 percent in ambient mercury concentrations. These data are further supported by research performed by Aucott, et al., in which it was shown that "between 17 and 40 percent of the mercury in broken low-mercury fluorescent bulbs is released to the air during a two-week period

immediately following breakage, with higher temperatures contributing to higher release rates."[35] The potential for lamp breakage outside the DTC device is inherent to device use. Possible release of and exposure to mercury vapor, as a result of broken lamps, is an important consideration as part of any operations managing fluorescent bulbs.

Because of the multiple potential sources of mercury being released during normal DTC device operations — during drum changes, through the degradation of seals over time (leading to leaks), possible leakage due to improper assembly or malfunction, and the breakage of lamps outside the DTC device, either during handling or feeding lamps into the device — a respirator was always available to the operator during the Study. Either use of a respirator, or continuous air monitoring for mercury with a mercury vapor monitor, such as a Jerome or Lumex, were the only ways to ensure that operator mercury exposures remained below the OSHA PEL and AGCIH TLV throughout the Study.[36]

7.2 Safety Concerns when Operating DTC Devices

Throughout the DTC Device Study, field observations were made and documented by the study team. These observations provide insight into potential safety issues and mitigation measures that were undertaken during the Study (and could be used by other device operators) to enhance the safety of operating DTC devices.

7.2.1 Operator Safety

As noted above, when lamps were being fed into the DTC devices, they would occasionally break and/or jam in the feed tubes. This was an issue common to all devices. Lamps sometimes broke before they could be fully fed into the devices, causing, in some instances, visible release of phosphor powder, as well as flying shards of glass. The configuration of the feed tubes on several devices exacerbated this problem, where, for example, the operator either had to lower the lamps to waist level or raise them up to shoulder level in order to insert them into the feed tube.

Various articles of personal protective equipment (PPE) were used by the study team during operation of DTC devices to ensure operator safety (*refer to Photograph 7. 1*). These included safety glasses, full-face shields, puncture-resistant (Kevlar®) gloves, hearing protection, and air-purifying, negative pressure respirators (when air monitoring readings were above pre-determined safe levels). Disposable Tyvek® coveralls were also worn by the DTC device operator and assistant, to reduce both skin exposure to the airborne mercury and the possibility of tracking mercury residues out of the testing facility.

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[35] *Aucott, Michael; McLinden, Michael; and Winka, Michael. 2003. Release of Mercury from Broken Fluorescent Bulbs. Journal of Air & Waste Management Association. 53: 143-151. The lamps used in this investigation were Phillips four-foot Econ-o-watt F40 CW/RS/EW, 0 8E bulbs, which are reported to contain 4.4 mg or 4.7 mg of mercury.*

[36] *The traditional hierarchy of occupational chemical exposure control specifies that engineering controls (i.e., adequate monitoring and ventilation) be used before relying on PPE.*

Photograph 7. 1: Clearing Jammed Feed Tube of Manufacturer A Device

Due to the possibility of mercury release from lamp breakage outside the DTC device or leaks from the DTC device, respiratory protection was always available to the operator and assistants throughout the Study and was used most of the time.

7.2.2 Number of Operators

During the Study, two people operated the DTC devices at each location. One person fed the lamps into the device, and the other person supplied the operator with full boxes of lamps, removed the empty lamp boxes, and handed lamps to the machine operator, allowing for efficiency in feeding lamps. While one person could probably operate the DTC device, the study team found it much easier and more efficient to use the two-person team. This was particularly important when it came to changing drums. Having a two person team available allowed drum changes to be performed much more securely and quickly (the Manufacturer B device required a two-person team to change drums, but the other devices did not). The advantages of a two-person team included both help in lifting the DTC off the full drum and positioning it correctly on the empty drum, as well as allowing the full drum to be more quickly covered and sealed.

7.2.3 Location and Ventilation for Lamp Crushing Activities

As discussed in Section 4.2, the background mercury concentrations in the industrial lamp crushing facilities were several orders of magnitude higher than background mercury concentrations that would be expected outside or in a building that is not associated with mercury processing activities, such as a home or an office building. One of the reasons that this Study was conducted at lamp recycling facilities was that these facilities already have safeguards in place to prevent exposure to visitors to the facility and to residents in the surrounding neighborhood.

These safeguards include a separate ventilation system for the offices, which does not cycle the air from the crushing area into the offices, and fume hoods on the industrial lamp crushers that vent fumes through carbon filters. The separate ventilation system protects the office workers from exposure to mercury. The production workers at the facility (i.e., those operating recycling equipment) are

aware of the potential of mercury exposure and have been trained in practices that will prevent mercury release and exposure. Production workers at lamp recycling facilities are required to have OSHA Safety Training. Additionally, material safety data sheets (MSDS) for mercury must be made available to these workers.

7.3 Potential DTC Design Modifications

Drum top lamp crusher design is an evolving field, and many aspects of device design can affect its ability to contain mercury (e.g., see Section 3.5.1). The devices tested in this Study are only the second generation of drum-top lamp crushers and, while they represent a significant improvement over the first generation of such devices, further improvements in design and operation procedures would be beneficial. [37] Based on operator observations, the following areas for potential improvements in DTC device design were noted by the study team:

- Development of Leak Detection Systems: As discussed above, DTC devices may develop undetected leaks and release significant amounts of mercury as a result. While a portable mercury vapor monitor can easily detect rising airborne mercury concentrations, these devices are expensive to purchase and operate, ranging from $15,000- $22,000. Development of an effective leak detection system, such as a continuously operating pressure monitor, may reduce the need for continuous monitoring of DTC devices in operation to ensure operator safety and compliance with regulatory standards.

- Improvement in Mercury Capture during Drum Change: Drum changes were identified in the Study as the routine activity with the highest potential for operator exposure to mercury concentrations above the PEL. None of the devices tested were capable of maintaining mercury concentrations below the PEL during drum changes, so improvements in device designs to reduce mercury releases during this operation would be very beneficial.

- Chemical Treatment of Released Mercury Vapor: Most of the mercury released from lamps in DTC devices is elemental mercury vapor, which is volatile at room temperatures. Elemental mercury reacts with sulfiding agents very readily and quickly under environmental conditions to form mercuric sulfide. Because mercuric sulfide is a solid (powder) at room temperature, its release to the air should be much easier to control than mercury vapor. Airborne mercury sulfide powder inside a drum would most likely settle into the crushed lamps in the drum or be captured by the pollution control media of DTC devices. Incorporating sulfiding-agent injectors into a device design could potentially reduce mercury release during all activities associated with DTC device use (except lamp breakage outside the device). The study team did not explore this possibility, so we are unable provide any specific design recommendations.

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[37] *Based on a 1994 EPA study, some of the first DTC device designs (not necessarily designs from the manufacturers that participated in this Study) may have used no mercury emissions controls.*

- Increase in the Amount of Pollution Control Used in the Device: The Manufacturer A device showed the best performance overall. This device used approximately 87 pounds of activated carbon, which most likely contributed to its good performance. The other devices included much less activated carbon in their air filtration systems (*refer to Table 5. 6 for the specifications of the pollution control media for each device*).

This Study was designed to assess the potential for operator exposure to mercury, while operating the four DTC devices tested. The areas of improvement noted above resulted from observations made by the study team in the course of testing the devices and preparing this report. This list is not meant to be exhaustive.

7.4 Future Areas for Study

There are several areas in which additional study would be beneficial:

- Environmental Impacts of DTC Device Use: DTC devices have the potential to be used in a wide variety of places. It is possible that the use of these devices will decrease the overall release of mercury to the environment by decreasing the uncontrolled disposal of mercury fluorescent lamps (i.e., disposal in a dumpster). Future research to assess the potential impacts of DTC device use could include:

  - How much the use of DTC devices can impact the total amount of mercury being released into the environment;
  - How much mercury is emitted from DTC devices for each lamp crushed or each drum full of lamps crushed;
  - Who (in addition to the operator) may be exposed to mercury releases related to operation of a DTC device;
  - How the emissions from DTC devices compare to the emissions from other mercury emissions sources, including industrial lamp recycling facilities; and
  - Whether significant amounts of mercury collect in areas where DTC devices are stored and operated.

- Mercury Release from DTC Devices during Non-operational Periods: The overnight tests conducted in this Study were inconclusive (*refer to Section 4.7*). Because it is probable that in many cases drums partially filled with lamps will be stored for extended periods of time, more information about the release of mercury from DTC devices which are attached to partially filled drums is needed in order to fully characterize the mercury exposure that could be realized as a result of the use of a DTC device.

- Mass Balance Study: A concrete relationship between mercury input and mercury retention and release was not established for any of the devices in the Mass Balance Study. The following factors should be considered if a future Mass Balance Study is undertaken:

  - Appropriate procedures for representative sampling of the crushed lamps in the drum need to be developed;

- A validated and approved test method for quantifying the mercury in whole unbroken lamps is needed, including the relative accuracy and error inherent in such a test;
- An approved test method for quantifying the mercury in the pollution control media (HEPA, carbon, and particle filters) is needed, including the relative accuracy and error inherent in such a test;
- A study design specific to measuring all system inputs and outputs, including the use of a clean-room and the measurement of emissions; and
- Wipe sampling procedures need to be improved, including pre and post sampling of the material used to construct the containment structure.

- Development of a Standard Test Method(s) for DTC Device Performance: A standard DTC device evaluation protocol that can be used by DTC device manufacturers would ensure that manufacturer performance data are generated in a consistent manner, under known conditions. A true evaluation of crusher performance can be developed only if the volume of the crushing room, the air exchange rate, the lamp crushing rate, the duration of crushing, and all sampling and analytical methods are known and validated. Absent this information, a poorly performing DTC device could be "tested" and shown to perform well with regard to operator exposure because the test was performed using unrealistic ventilation rates or room size or was performed outdoors. Evaluating DTC performance under consistent, known conditions would also allow meaningful comparison of the performance of different lamp crushers. A standardized test method would help ensure the repeatability and accuracy of any tests results .

- Investigation of Mercury Release through Different Lamp Management Methods: This Study only examines mercury release from fluorescent lamps as a result of the use of DTC devices (as measured by operator exposure). When lamps are handled and recycled as whole lamps, there is the potential for breakage and, therefore, the potential for mercury release, during the storage and shipping of the lamps. Information about the frequency of breakage and the amount of mercury released when whole lamps are stored and then shipped to a recycler is needed in order to compare these different lamp recycling methods. Additionally, more information on releases of mercury resulting from disposal of lamps would provide a useful baseline with which to compare releases due to recycling.

- Aerosolization of Mercury: Additional study may be appropriate to determine whether aerosol mercury was not detected using the MCE filters because no aerosolization occurred or because any aerosol mercury collected on the filter was vaporized by the sampling vacuum pump.

7.5 Conclusions

The potential use of DTC devices involves a number of trade-offs. Spent mercury lamps contain elemental mercury, some of which is released to the air when lamps are broken. If thrown into a dumpster for disposal at a municipal solid waste landfill, breakage will occur either in the dumpster or at the landfill. In either case, a portion of the mercury contained in the lamps is immediately released to the

environment by volatilization, and the remaining mercury is available for release to the environment, over time, by leaching or in landfill gas.

Recycling of spent lamps represents one of the best ways to control the release of mercury to the environment from landfilling of fluorescent lamps, by keeping mercury out of landfills in the first place. Recycling can be done either on an individual lamp basis (i.e., sending whole, boxed lamps to a recycler), or by using a DTC device at the point where lamps are removed from service. Use of DTC devices has obvious appeal in that the devices reduce lamp volume, allowing several hundred crushed lamps to occupy the space that 40 or 50 whole lamps would occupy, thereby reducing storage and shipping costs. This leads to a reduction in recycling costs on a per-lamp basis. Crushing lamps before shipment also has the advantage of allowing shipping to the recycler in a well-sealed, durable container that is unlikely to release substantial amounts of mercury during shipment, while whole lamps may be broken during shipment and release mercury.

The DTC devices evaluated as part of this Study all released some mercury when used and so have the concern of creating new mercury exposures. The mercury released during DTC device use will inevitably create certain new mercury exposure situations. The DTC device operator and any assistants handling lamps or working directly with the DTC device are the most obvious new exposures. Less direct mercury exposures that could be created by DTC device use include anyone working in or visiting buildings in which DTC devices are used. The only way to eliminate these unnecessary indirect mercury exposures would be to keep the ventilation of the lamp crushing room completely separate from the general building ventilation system as is done at industrial lamp recycling facilities.

The data collected in the course of this Study indicate that none of the DTC devices evaluated completely controlled mercury emissions during lamp processing operations, even with optimal operation. The Study further indicates that maintaining optimal performance consistently over years of DTC device use for the current generation of devices will be challenging. Even generally well designed devices released mercury in routine use, particularly during drum changes. Device malfunctions increased mercury release by a small amount (i.e., when lamps jammed in the feed tube) or by a significant amount (i.e., when the flange gasket was not included in assembly). Use of a poorly designed device could result in mercury exposures nearly an order of magnitude above the OSHA PEL. Fundamental design changes to reduce the reliance on fallible components (such as seals) would be needed to improve the ruggedness of drum-top crushing devices.

Office of Solid Waste and Emergency Response
1200 Pennsylvania Avenue, NW
Washington, DC 20460
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