

# Estimating Regional Material Flows for LCDs

Proceedings of the IEEE International Symposium on Electronics and the Environment ISEE (May 2008)

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**Abstract**—As LCD monitors increasingly enter the e-waste stream, there is a need to better understand what recyclers might expect in terms of what they will receive and what materials they will need to manage. Here, we identify materials used in the production of key subassemblies, and note uncertainties in the composition of the LCD assembly, film set (comprised of the reflection foil, light guide, prism foil, diffuser, and the brightness enhancement film), and the backlight assembly. Next, we quantify the range of U.S. flows of LC assembly and film set materials and the mercury in the backlight assembly, on the basis of the range of screen diagonals for portable PCs, PC flat screens, and TV flat screens. Finally, we considered computer use statistics presented by the U.S. Census and data on the location of U.S. e-waste and automotive mercury switch recovery programs as a first step in understanding regional preparedness, noting opportunities for improvements in all aspects of our analysis.

**Index Terms**—E-waste, environmental factors, liquid crystal displays, material quantification, recycling

## I. INTRODUCTION

Estimates show that the quantity of waste liquid crystal display (LCD) monitors will surpass waste cathode ray tube monitors as early as 2009 [1]. Thus, there is a growing need to understand what regional e-waste recyclers should expect, both in terms of receipts and materials management needs.

A number of studies have focused on determining the materials that constitute a typical LCD. One of the earliest studies was presented by Mizuki and Schult in 1998, based on a disassembled 15-inch diagonal LCD monitor [2]. Results include information on the quantity, material, weight, formation process, features, supplier and finish for the LCD monitor. Although the information presented in the study is well-documented, the age of the study and the continuing changes in LCD design suggest there needs to be an updated and accounting of possible variations in LCD materials.

Information from Mizuki and Schult's work was used to perform a life cycle assessment (LCA) of desktop computer

monitor [3] in 2001. LCD materials (types and quantities) were gathered using primary manufacturing data from LCD component manufacturers in Asia and the US. An important point made in the study was that the final mass quantities included the total materials inputs during the manufacturing process, meaning that they include both the component materials as well as manufacturing waste and excess materials. This LCA is by far the most cited study in assessing the environmental aspects of materials for LCD monitors.

The study by Mizuki and Schult also provides the basis of assessments of the toxicity of LCD materials and waste LCD material flows [4,5], published as recently as 2007. Other related LCD research has focused on material and manufacturing alternatives for flat panel displays [6] and physical disassembly of LCDs to determine value relationships between quantity and time for disassembly and segregation or develop web-based models that provide environmental impact scores for different electronic products [7,8]. Although much of the information provides a baseline for understanding LCD materials flows, due to rapidly changing designs, a good portion of the information is out-dated.

With end-of-life LCDs soon numbering higher than CRTs, it is important to determine the composition of LCDs, taking into consideration design changes (e.g., in response to e-waste directives) and variations in monitor size. Currently, many LCD recyclers only remove the mercury backlight (the most common hazardous material in LCDs) and then shred the LCD panel with the bulk of the monitor. The reason for doing this is primarily because LCD recycling techniques are still quite limited [4].

The first part of this paper identifies LCD components and materials. This forms the basis of a preliminary quantification of LCD materials. Finally, the quantification of LCD materials forms the basis for the estimation of regional materials flows and regional recycling infrastructure issues.

## II. MATERIALS ASSESSMENT

### A. Identification of LCD Materials

As shown in Figure 1, a LCD monitor is comprised of a front frame, the LCD assembly, plastic housing, film set, back frame, backlight assembly, a power supply and controller, a rear cover, and a base/stand [3, 6, 9, 10]. The monitor is built around the LCD assembly, which is based on a liquid crystal (LC) mixture sandwiched between two glass substrates with polarizers on the outer sides. The inner sides consist of thin film transistors (TFTs) on one glass substrate, color filters on the

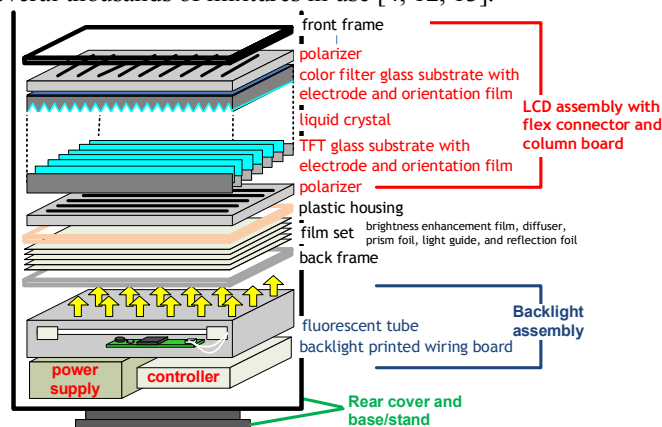
This work was supported in part by the U.S. National Science Foundation under Award No. 0628190.

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other substrate, with conductive electrodes and orientation films (a.k.a. alignment layers) on both sides of the LC mixture.

The standard in TFT-LCDs includes nematic and thermotropic **LC materials** [11]. Because a single LC compound does not fulfill the complex requirements of the displays, compound mixtures are used to optimize physical and chemical properties for specific applications. LC mixtures in a typical LCD usually contain about 10 - 25 compounds, with several thousands of mixtures in use [4, 12, 13].



**Fig. 1 LCD Monitor Subassemblies**

Today 69% of LCs are prepared by Merck KGaA in Germany, holding ~2,500 patents on LCs and mixtures. Merck is followed by Chisso Corporation and DIC Corporation at a combined 21% of the world LC market, with the balance of manufacturers primarily in China who often use Merck's older "recipes" [14]. Our review of 100+ LC compounds prepared by Merck, DIC Corporation and Chisso Corp. and available through Sigma-Aldrich [15] identified aromatic-based polymers (with a total of 14 to 30+ carbon atoms) selectively adding oxygen, nitrogen (sometimes as a cyano group), fluorine, nitrogen, bromide, and chlorine atoms [16-30].

On both sides of the LC mixture are conductive electrodes and orientation films. **Conductive electrodes** are made from indium tin-oxide. **Orientation films** are made from polyimide or diamond-like carbon [6, 9]. These are commonly deposited as part of the color filter and TFT layers.

The LC mixture, conductive electrodes and orientation films are sandwiched between two glass substrates with polarizers on the outer sides. **Polarizers** are layered films starting with a layer of PET, a layer of tri-acetyl cellulose, the polarizer layer of stretched polyvinyl alcohol doped with iodine or unspecified dyes, a second layer of tri-acetyl cellulose, an acrylic-based adhesive, and a final PET layer. The polarizer market is currently dominated by Nitto Denko, who has captured 35% of the total market share for several years. The rest of the polarizer market is dominated by Optimax, Sumitomo, LG Chemical, and Santriz.

Several types of materials have been used for display **glass substrates** since the first generation of glass substrates was introduced. Some examples of glass substrate materials include alkaline-earth aluminosilicate, alkaline earth boro-aluminosilicate, barium aluminoborosilicate, barium borosilicate and soda lime [6].

Corning Inc. is the current leader in display glass technology and sets the industry standard with other market leaders include Asahi Glass, Nippon Electric Glass (NEG) and NH Techno Glass (NHT), all Japanese companies. The latest LCD innovation from Corning is the EAGLE XG™ glass substrate which is free of arsenic, antimony and barium and at the same time is lighter, more durable and has advanced thermal properties when compared to its predecessors [31].

On the glass substrate at the front of the monitor, the **color filter** consists of a black matrix, colorants, an overcoat layer, and the conductive electrode [32] with material options presented in Table 1. In some fabrication methods, the overcoat is omitted. The top manufacturers of CF materials are Dai Nippon Printing, Photronics and Toppan Printing.

**Table 1. Materials for Color Filters [32-41]**

Color Filter Layer	Materials Identified
Black matrix	Cr, Ni, black polymer resin, black chrome (Cr/CrO or Cr/CrO <sub>2</sub> ), Fe/FeO <sub>x</sub> , Mo/MoO <sub>x</sub>
Color filter colorants	Dyes or pigments
Photopolymers/binders	Gelatin, casein, acrylic, polyimide, polyvinyl alcohol, epoxy, melamine, polyester
Overcoat layer	Transparent acryl resin, polyimide resin or polyurethane resin
Conductive electrode	Indium tin-oxide

Finally, on the inner glass substrate is the **TFT layer**. The TFTs consist of three terminals: the gate, source and drain. The structure also consists of a semiconductor layer between the gate and source/drain. The resulting layers are the gate electrode or select busline, gate insulator, semiconductor, ohmic contact, source/drain electrode or data busline and passivation layer, with Table 2 listing TFT layer material options.

**Table 2. Materials for TFT layers [3, 6, 9, 42-45]**

TFT Layer	Materials Identified
Gate electrode and source/drain electrode,	Refractory metals (Ta, Cr, Mo, W), Ti, Cu, Al, Al alloys, Ta-Mo, Mo-W, Cr-Ni, Ti-Mo, Mo-Al, Ti-Al-Ti, other dual or triple layers
Gate insulator (dielectric)	SiN, SiO, SiN <sub>x</sub> , SiO <sub>2</sub> , SiO <sub>x</sub> N <sub>y</sub> , Si <sub>3</sub> N <sub>4</sub> , Ta <sub>2</sub> O <sub>5</sub> , Al <sub>2</sub> O <sub>3</sub> , dual dielectrics
Semiconductor	a-Si:H
Ohmic contact	n+ a-Si:H
Passivation layer	SiN, Polymer overcoat
Conductive electrode	Indium tin-oxide

Moving inward from the LC assembly is the plastic housing (polymer unknown) and the film set followed by a back frame made from aluminum or magnesium alloys. The **film set** is defined here to include the reflection foil (a.k.a. the diffuse reflector), the light guide, the prism foil, the diffuser, and the brightness enhancement film (BEF) [9-10], [46-52]. Table 3 lists film set materials, with a major manufacturer being 3M.

Finally, the backlight assembly includes a circuit card assembly and a light source, typically based on one or two mercury vapor lamps. In mercury vapor lamps, the mercury acts as the light source within a fused quartz inner tube. The inner tube is within an outer tube made from borosilicate glass with a phosphor coating. The assembly also includes a silicon rubber shock cushion and a cable assembly. Xenon arc lamps are also used, and can combine xenon with mercury as the light

source. The assembly includes a fused quartz arc tube and electrodes of thorium-doped tungsten with molybdenum or invar alloy at the interface, and again a silicon rubber shock cushion and a cable assembly. In both cases, the tubes extend the length of the display, and are particularly thin and fragile. [9, 53-55]. Inorganic LEDs are a newer option and are based on a wide array of semiconductor materials (see Table 4), have an anti-reflective coating of unknown constituents, and would also require a cable assembly. For example, apparently NEC's LCD2180WG-LED is a 21" LCD monitor backlit by red, green, and blue LEDs that produce an extremely pure white [56].

**Table 3. Film Set Materials**

	Materials Identified
BEF	Polymeric particles, light-directing materials
Diffuser	Polyester polymer, methacrylic resin, styrenic resin, cyclic olefinic resin, acrylic coating, polyvinylidene chloride, unspecified antimony, titanium, and germanium compounds
Prism foil	No information found
Light guide	PMMA (Plexiglass), polycarbonate, cycloolefin-type resin, SOL-GEL (proprietary moldable glass), other unspecified moldable transparent materials, unspecified doping particles, acrylic resin, selenium, gold-chloride
Reflection foil	PET with unspecified microlenses, lenslets, polymeric film, and microbeads (polymeric spheres)

Table 5 summarizes potential issues associated with LCD materials. Given that the materials in the plastic housings and frames, the power supply, and the controller can be expected to be very similar or the same as those facing a very broad range of e-waste (e.g., CPUs, etc.), new challenges are presented by the LC assembly, the film set, and the backlight assembly. Further, aside from the assessment of select materials presented by the Eastern Research Group [4], little assessment and no Toxicity Characteristic Leaching Procedure (TCLP) data were found for these subassemblies or for LCD monitors in general. The greatest uncertainties lie in the LC assembly and the film set, with the remainder of material concerns being similar to those of other e-waste.

**Table 4. Inorganic LED Semiconductor Materials [57]**

LED Inorganic semiconductor materials	Colors produced
Sapphire (Al <sub>2</sub> O <sub>3</sub> )	blue
Silicon carbide (SiC)	blue
Zinc selenide (ZnSe)	blue
Aluminium gallium phosphide (AlGaP)	green
Gallium nitride (GaN)	green, pure or emerald green, and blue
Gallium nitride (GaN) with an AlGaN Quantum Barrier	white
Aluminium gallium indium phosphide (AlGaInP)	high-brightness orange-red, orange, yellow, and green
Aluminium gallium arsenide (AlGaAs)	red and infrared
Gallium arsenide phosphide (GaAsP)	red, orange-red, orange, and yellow
Gallium phosphide (GaP)	red, yellow and green
Aluminium gallium indium nitride (AlGaInN)	near ultraviolet
Aluminium gallium nitride (AlGaN)	near to far ultraviolet
Aluminium nitride (AlN):	near to far ultraviolet
Indium gallium nitride (InGaN)	near ultraviolet, bluish-green and blue
Diamond (C)	Ultraviolet

**Table 5. Summary of LCD Materials of Potential Concern**

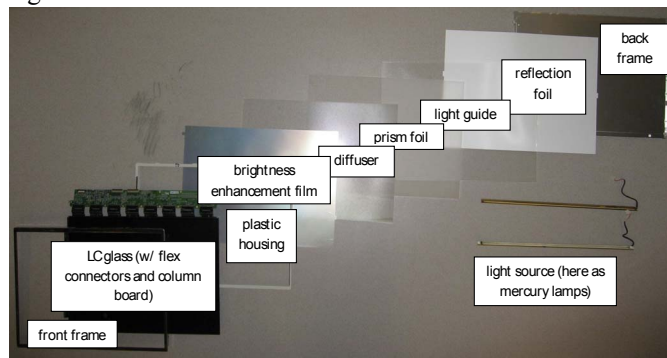
Subassembly	Potential Materials of Concern	Status
LC assembly	LC polymers including cyano groups, fluorine, chlorine, and bromine; conductive electrodes including indium-tin oxide; polarizer polyvinyl alcohol doped with iodine or unspecified dyes; color filter heavy metals, unspecified dyes/ pigments; and TFT layer heavy metals	Unknown constituents
Film set	Heavy metals, unknown polymers and coatings	Unknown constituents
Backlight assembly	Mercury in light tubes, gallium arsenide, phosphors and heavy metals in LEDs	Within a very fragile fluorescent tube
Plastic housings and frames	Brominated flame retardants, plastic polymers	Concerns are similar to those of other e-waste
Power supply and controller	Heavy metals	Concerns are similar to those of other e-waste

For the LC assembly, the LC materials are the most uncharacterized. Each of the 3 primary LC manufacturers has environmental information on their websites. Merck provides toxicology and ecotoxicology information, as well as those for Chisso and DIC [58-59]. Their LCs are not acutely toxic nor mutagenic, but little quantitative data is provided regarding this issue. Also note that despite the availability of hydrocarbon LC compounds, polymers including cyano groups, fluorine, chlorine, and bromine may be of concern for e-waste recyclers.

Finally, the mercury in the backlight assembly can be expected to be of concern and is required to be managed by mercury recovers. LEDs offer an alternative, which should be more durable during monitor disassembly processes but may introduce issues related to gallium arsenide and heavy metals.

### B. Quantification of Materials per LCD Monitor

Next, we quantified LC assembly and film set materials and the mercury in the backlight assembly, leaving both the quantification of the remaining LCD materials (with concerns similar to those of other e-waste) and assessment changes in flows due to the switch from CRTs to LCDs (and ultimately including plasma monitors) for future work. We based our assessment on assumed ranges of LCD diagonals and the screen area, noting the very strong relationship between the amount of LC assembly and film set materials and mercury as depicted in Figure 2.



**Fig. 2 Components sized by the diagonal**

The data used to quantify LCD materials are presented in

Table 6. The range of diagonals and associated areas for each type of LCD monitor (portable PCs or notebook computers, PC flat screens or desktop computer monitors, and TV flat screens) were obtained from Prismo Mobile [60] Area-based densities were estimated using screen area, thickness and material density information.

**Table 6. Data Used in Materials Quantification**

	density (g/cm <sup>2</sup> )	Portables		PC Flat Screen		TV Flat Screen	
		minimum	maximum	minimum	maximum	minimum	maximum
diagonal (inches)		12.1"	20.1"	15"	40"	15"	40"
area (cm <sup>2</sup> )		4.32E+02	1.17E+03	6.97E+02	4.96E+03	6.97E+02	4.96E+03
<b>LC Assembly</b>		<b>mass (g)</b>					
Glass	1.91E-01	8.27E+01	2.24E+02	1.33E+02	9.49E+02	1.33E+02	9.49E+02
Electrode	7.00E-05	3.02E-02	8.20E-02	4.88E-02	3.47E-01	4.88E-02	3.47E-01
Alignment layer	1.00E-05	4.32E-03	1.17E-02	6.97E-03	4.96E-02	6.97E-03	4.96E-02
Liquid crystals	6.00E-04	2.59E-01	7.03E-01	4.18E-01	2.97E+00	4.18E-01	2.97E+00
Spacers	5.00E-07	2.16E-04	5.86E-04	3.49E-04	2.48E-03	3.49E-04	2.48E-03
<b>LC Assembly total</b>		<b>8.29E+01</b>	<b>2.25E+02</b>	<b>1.34E+02</b>	<b>9.52E+02</b>	<b>1.34E+02</b>	<b>9.52E+02</b>
<b>Film Set</b>		<b>mass (g)</b>					
Brightness enhancement film	6.83E-02	3.22E+01	8.89E+01	4.95E+01	3.52E+02	4.95E+01	3.52E+02
Diffuser	6.83E-02	3.22E+01	8.89E+01	4.95E+01	3.52E+02	4.95E+01	3.52E+02
Prism foil	6.83E-02	3.22E+01	8.89E+01	4.95E+01	3.52E+02	4.95E+01	3.52E+02
Light guide	4.76E-01 to 9.52E-01	2.25E+02	1.24E+03	3.45E+02	4.91E+03	3.45E+02	4.91E+03
Reflection foil	6.83E-02	3.22E+01	8.89E+01	4.95E+01	3.52E+02	4.95E+01	3.52E+02
<b>Film Set total</b>		<b>3.54E+02</b>	<b>1.60E+03</b>	<b>5.44E+02</b>	<b>6.32E+03</b>	<b>5.44E+02</b>	<b>6.32E+03</b>
<b>Backlight Assembly</b>		<b>mass (g)</b>					
Mercury	0.00E+00	2.46E-03	6.67E-03	3.97E-03	2.82E-02	3.97E-03	2.82E-02

**C. From LCD Materials to Regional Materials Flows**

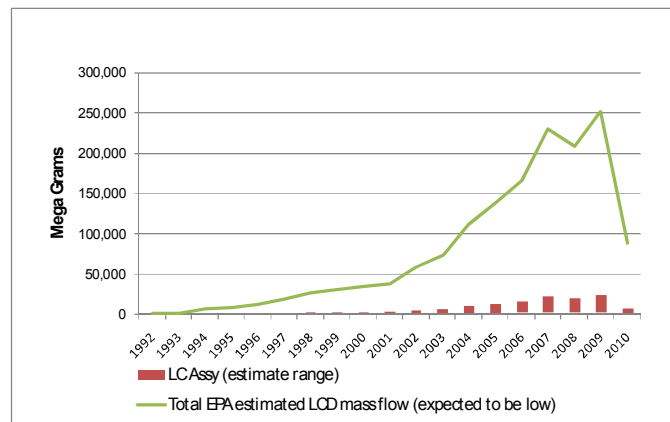
To move from the materials per LCD monitor to national flows, we used U.S. LCD retirement data (including the number of units and tons per year estimated by the U.S. EPA to estimate the annual national flows of LC assembly, film set, and mercury in retired monitors from 1992-2010 [1]. These data are presented for portables, PC flat screens, and TV flat screens. Data for portables assumes a reduction in the overall mass of units from ~4,000 g in 1992 to ~3,000 g in 2010. Data for PC flat screens and TV flat screens however are assumed to remain constant throughout the timeframe, at 11,158 and 13,154 g/unit respectively [1].

Finally, given our interest in characterizing regional LCD monitor recycling issues within the context of materials flows, we considered computer use statistics presented by the U.S. Census as well as data on the location of U.S. e-waste and automotive mercury switch recovery programs. Specifically, the U.S. Census data on computer and internet use combines use at home, at work, and in school divides results among 4 U.S. regions: the northeast, midwest, south, and west [61]. The only assumptions required to develop our data summary was that households with 2 or more computers were assumed to have on average 2.5 computers and that the number of students per computer at schools was 3.9 [62]. Note that similar data for U.S. TV use were not found. Next, we summarized state e-waste recycling data presented by the Electronics Industries Alliance to match the U.S. Census regions. Finally, we summarized End of Life Vehicle Solutions (ELVS) Corporation's mercury switch recovery program state data [63], again to match the U.S. Census regions, assuming mercury switch recovery in vehicles is somewhat like what would be needed for LCD backlights given that they also must be carefully removed (although from a vehicle) and subsequently packaged and transported to a management facility. ELVS was created pursuant to the U.S. National Vehicle Mercury Switch Recovery Program by ten automakers to provide dismantlers with information and supplies needed for switch removal, and

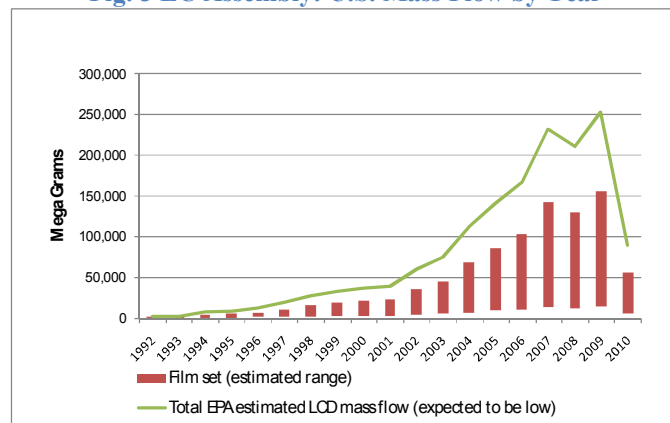
collect and transport switches to proper recycling and disposal facilities performance [64].

**III. RESULTS**

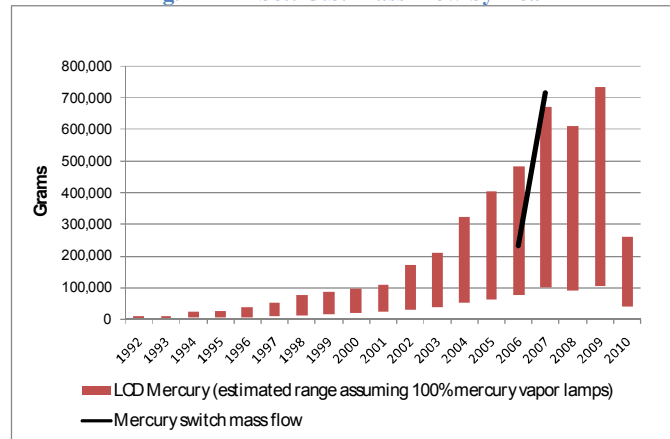
The combination of the LC assembly, film set, and mercury estimates and the U.S. EPA LCD monitor retirement projections are presented in Figures 3-5.



**Fig. 3 LC Assembly: U.S. Mass Flow by Year**



**Fig. 4 Film Set: U.S. Mass Flow by Year**



**Fig. 5 LCD Mercury: U.S. Mass Flow by Year**

All material masses are presented as a range of values, based on the data in Table 6 for the minimum and maximum diagonals and assuming the use of mercury backlight assemblies. Thus all extremes are highly unlikely and the true values lie somewhere within. Next, Table 7 presents the characterization of regional issues.

**Table 7. Regional Characterization**

	US Census 2003 % of US computer use	Indicators of Capacity to Manage		
		E-Recycling Programs	# of E- Recycling Programs (% for region)	Mercury Switch Recovery
		#E-waste programs/ 100,000 people		Switch Recovery: ave. units/ yr; ave. kg Hg/ yr (% for region)
Northeast	19%	1.10	573 (25%)	108,954; 109 (23%)
Midwest	23%	0.72	448 (20%)	132,103; 132 (28%)
South	34%	0.56	543 (24%)	60,309; 60.2 (13%)
West	24%	1.11	698 (31%)	173,597; 173 (37%)
US total		0.82	2,262	474,962; 474

#### IV. DISCUSSION

Figures 3 and 4 present the mass of the LC assembly and the film set, as well as U.S. EPA estimates for the total LCD monitor materials flows. In all years, the amount of LC assembly and film set materials (assumed to contain unknown constituents as noted in Table 5), represent between 33 and 36% of the total monitor mass and dominated by the film set. However, we assume that the U.S. EPA estimates for the total monitor mass to be conservative since they determined the value to be only a best estimate for lack of further information. Further, an improved characterization of film set materials and encouraging LCD monitor manufacturers to mark film set components for recycling would assist in planning by e-waste recyclers.

Figure 5 presents the expected LCD mercury flows as well as the mass of mercury in vehicle switches collected in 2006 and 2007 by ELVS. As shown, based on the assumptions applied, the mass of LCD mercury can be expected to be of the same order of magnitude as that currently collected by ELVS. However, the efforts of ELVS and the U.S. National Vehicle Mercury Switch Recovery Program are intended to complement existing state mercury switch reduction efforts (although no data were found on such efforts) to help reduce up to 75 tons of mercury emissions over the next 15 years from vehicles manufactured prior to 2003 [64]. It may be possible to leverage the vehicle switch recovery infrastructure in the management of LCD mercury, however this option should be compared to the benefits of basing backlight assemblies on xenon and LEDs.

We are interested in improvements to materials identification and quantification, and the estimation of regional materials flows. As we continue, we will quantify materials within the context of design variants and generational changes based on previous work by Cooper [65]. Specifically, Cooper describes a method to determine material mass as a function of performance from a baseline material an emerging alternative based on performance drivers.

The regional characterization in Table 7 shows that the expected percentage of U.S. computer retirements in the midwest and south are higher than the current commensurate percentage of e-waste recycling programs and efforts in mercury switch recovery, with the opposite situations in the northeast and west. This might mean that interregional transport can be expected in the short term, and infrastructure

development is needed in the midwest and south to manage longer term flows. However, U.S. estimates of the LCD monitor retirement need to be improved and expanded to include TVs. An alternative structure for the estimation of monitor retirement is planned for our continuing research in partnership with researchers at Georgia Tech. We are interested in estimating monitor use patterns based on urban planning data founded in an input-output analysis of national flows. We are also interested in understanding how monitors and materials move in and out of regions as related to regional job opportunities and transport impacts and hazards.

#### V. CONCLUSIONS

LCD recycling is still a relatively new effort, with many unknowns in the composition and quantity of materials in each display. For each component, there are a small number of manufacturers but with a variety of materials being used in the manufacturing process. Many components have witnessed little generational changes, which will assist in further characterizing materials. An immediate opportunity exists to encourage subassembly marking for recycling/management. In addition to national estimates, regional estimates also have to be improved, considering the viability of related business models.

#### ACKNOWLEDGMENT

Special thanks are due to Lisa Sepanski of the King County (WA) Solid Waste Division, Craig Lorch of Total Reclaim and the "Modeling Material Flows for Sustainable Industrial Systems for Urban Regions" team at the Georgia Institute of Technology.

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