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ENVIRONMENTAL, HEALTH AND SAFETY ISSUES RELATED TO COMMERCIALIZING $CuInSe_2$-BASED PHOTOVOLTAICS

Chris Eberspacher,* Vasilis M. Fthenakis, and Paul D. Moskowitz
*UNISUN, Newbury Park, California

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ANALYTICAL SCIENCES DIVISION

DEPARTMENT OF APPLIED SCIENCE

BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

SUMMARY

Photovoltaics technology is rapidly evolving towards a new generation of low-cost thin film technologies. One of the most promising materials in this new generation is copper indium selenide ($CuInSe_2$ or CIS). As with any new material, successful commercialization of CIS photovoltaic (PV) technology will require attention to environmental, health and safety issues, including consideration of the sources, usage, and end-of-product-life disposal and/or recycling of the constituent materials.

This work focuses on three specific environmental, health and safety (EH&S) issues related to CIS PV: (1) economics are analyzed to determine their impact on materials use and re-use; (2) Federal and California State environmental disposal and waste handling regulations are analyzed to evaluate their impact on PV module manufacturing and end-of-life module handling; and (3) the logistics and economics of product recycling and waste disposal by industries with comparable EH&S issues are examined to quantify the corresponding options available for handling, disposing of and/or recycling manufacturing byproducts and end-of-life modules.

Materials economics suggest that it is unlikely that CIS PV modules can be economically recycled for their materials value alone. Direct materials costs are a substantial fraction of the projected production costs of thin-film CIS PV products; however, given the low recovery rates and salvage values of the materials in a CIS PV module, it is unlikely that materials availability will alone economically warrant end-of-module-life materials recovery. The maximum likely materials reclaim value of a CIS PV module is 1 - 3 ¢/W.

Under Federal and California State environmental regulations, end-of-life CIS PV modules will likely be solid wastes unless handled in a manner that qualifies for exclusion, e.g. certain types of reclamation. Under Federal regulations, CIS PV modules will likely be classified as non-hazardous provided the modules do not exhibit hazardous "characteristics", notably the toxicity characteristics. Under California regulations, CIS PV modules will likely be classified as hazardous if they receive an exception for exceeding the Total Threshold Limit Concentration (TTLC) for selenium. Used CIS modules will likely be unregulated non-hazardous trash if an exclusion or reclassification for Se TTLC is granted, and will likely be exempt from hazardous waste regulations when recycled. Un-used defective CIS plates will likely be exempt from Federal regulation if reclaimed as an "unlisted commercial chemical product", and can probably undergo in-house physical separation as pre-treatment for reclaim. Various processing byproducts will likely be RCRA-exempt if reclaimed as "unlisted byproducts".

A workable PV module recycling program will require careful attention to regulatory framework, materials economics, and the experiences of comparable industries. Collection and consolidation of used PV modules will be greatly simplified if used modules are returned to the manufacturer or a contracted recycling center as

"products" destined for (potential) refurbishment as PV modules. Reverse logistics companies are already in place nationwide to collect, consolidate and transport goods to manufacturers and/or recyclers. The collection of decommissioned PV modules is probably feasible in the case of large, centralized installations. The collection of dispersed modules in small, remote and/or consumer applications will be problematic. Multi-materials recyclers such as those entities active in electronics and telecommunications equipment recycling may be useful participants in PV module recycling efforts even if PV modules fail to provide the component salvage and precious metals reclaim values that normally support recycling in those fields. The projected economics of recycling CIS PV modules range from ~0 to 8 ¢/W depending on the specific methods, participants and regulations of recycling.

Analysis and testing of module samples by potential recyclers will be necessary to provide the base of knowledge needed to accurately project the technical and economic prospects for cost-effectively recycling PV modules.

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1 INTRODUCTION

Photovoltaics (PV) technology is a versatile power source suitable for many applications. PV power modules are already cost-effective in a wide variety of remote and stand-alone applications, and, as PV module costs continue to decrease, PV power will become cost-effective for many more of the world's energy needs.

Photovoltaics technology is undergoing a rapid transition, evolving from the traditional products based on crystalline silicon to a new generation of low-cost products based on thin films of photoactive materials deposited on inexpensive substrates like ordinary window glass. One of the most promising materials in this new generation of thin film PV technologies is copper indium selenide ($CuInSe_2$ or CIS).

CIS is not yet a widely-used semiconductor, but it is ideal for photovoltaic applications. CIS absorbs visible light very strongly, and very thin films (e.g. $<1\ \mu m$) are sufficient to absorb most sunlight. Small-area thin film CIS solar cells have been fabricated with sunlight-to-electricity conversion efficiencies above 17%, comparable to the best crystalline silicon solar cells in large-scale manufacturing today (NREL-95). Large-area monolithic integrated CIS modules have been fabricated with efficiencies of ca. 10.5%, comparable to crystalline silicon modules commercially available today (SSI-92). Given the low manufacturing costs possible with thin film processing techniques and the high efficiencies of CIS photojunctions, it is widely anticipated that in full-scale production CIS PV modules will be very competitive in both performance and price.

Companies, universities and government laboratories in the United States, Asia and Europe are working to develop CIS PV technology. CIS PV modules are not yet commercially available in the U.S., but several companies are soliciting capital investors to fund commercial production. The National Renewable Energy Laboratory (NREL) in Colorado is seeking to license its CIS PV technology in order to accelerate the entry of CIS into the commercial PV market.

Given the good prospects for CIS PV technology being commercialized in the near future, it is an opportune time to quantitatively consider the Environmental, Health and Safety issues related to CIS commercialization. This report summarizes a study of a cross-section of these issues by UNISUN. This work was funded by Brookhaven National Laboratory under the aegis of the U.S. Department of Energy.

2 STUDY TASKS

The environmental, health and safety (EH&S) field is quite broad. The basic issues related to PV commercialization span manufacturing, product use, marketing and sales, and end-of-life disposal and/or recycling (Table 1).

Table 1. Basic EH&S Issues Related to PV Commercialization
- Can the product be made safely and cost-effectively?
- Can the product be used safely and effectively?
- Can the product be marketed and sold profitably?
- How should the product be handled at end-of-life?

This work focuses on three specific EH&S issues related to CIS PV (Table 2). CIS PV economics were analyzed to determine their impact on materials use and re-use. Federal and State environmental disposal and waste handling regulations were analyzed to evaluate their impact on PV module manufacturing and end-of-life module handling. The logistics and economics of product recycling and waste disposal by industries with comparable EH&S issues were examined to quantify the corresponding options available for handling, disposing of, and/or recycling manufacturing byproducts and end-of-life modules.

Table 2. Issues Addressed in the Project
- Impact of CIS PV cost structure, materials resources and materials supplies on materials use and re-use
- Impact of EH&S regulations on CIS PV manufacturing and marketing
- Logistics and economics of end-of-life CIS PV module recycling and/or disposal

3 COST STRUCTURE, MATERIALS RESOURCES AND MATERIALS SUPPLY

Production cost estimates for CIS PV modules are in the range of $0.5 - 1.5/W at production volumes of 10 - 20 MW/yr, and CIS PV technology promises to be very competitive with crystalline silicon PV technologies with reported manufacturing costs of $2 - 4/W (UNISUN-94a). Counter-intuitively, direct materials costs are a substantial fraction of most thin-film PV technologies. In the case of CIS, materials costs are 35 - 45% of the total projected module manufacturing costs. Of this fraction, glass for substrates and cover sheets account for about one third, and the active thin-film electrodes and semiconductor junction materials account for an additional one quarter to one third. Indium is the most costly of the thin-film material constituents, accounting for 2.5 - 5% of the total projected module cost. As will be discussed in detail below, this absence of any key recoverable cost driver material makes it unlikely that materials availability will economically warrant end-of-module-life materials recovery.

Overall materials supply is, however, an important issue for the long-term contribution of CIS PV technology. The primary constituent materials of a CIS PV module vary widely in their sources, current supplies and estimated worldwide reserves (Table 3). When CIS PV production grows to ca. 100 MW/yr - roughly equal to the projected worldwide annual photovoltaics production by the late 1990's - then CIS PV production will represent only 1 - 2% of the worldwide annual consumption of indium and gallium. Such comparatively low levels of PV manufacturing consumption will be unlikely to have any major impact on the overall availability or prices of these materials.

However, the current estimated worldwide reserves of indium and selenium do pose challenges for the long-term, very large scale production of 1995-vintage CIS PV modules. Worldwide reserves of indium in zinc ores are estimated at 2300 - 4600 metric tons, equivalent to 100 - 200 GW of CIS PV modules using present module designs. The CIS PV industry could consume this entire amount in roughly 40 years at a compound growth rate of 15%/yr typical of the past two decades of growth in the photovoltaics industry. The total of 200 GW production is less than a third of the 700 GW of installed electrical capacity in the United States alone. The situation for selenium is somewhat better. Estimated worldwide reserves of selenium could make about 3000 GW of CIS PV, comparable to the 2700 GW of worldwide installed electrical capacity. Thus in the case of both indium and selenium, the ultimate quantity of CIS PV modules might be limited (e.g., to ca. 200 GW cumulative production in the case of indium) by materials reserves. This suggests that one should consider options for minimizing the consumption of these materials and/or recovering these materials from end-of-life modules.

It is important to note that the supply limitations of indium and selenium are subject to a significant uncertainty, namely that both indium and selenium are presently recovered as byproducts of zinc and copper refining, respectively. As byproduct materials, supply and pricing are at best uncertain and dependent on other quasi-independent variables (e.g. on the price and demand for zinc and copper). It is also important to note that the supply limitations of indium and selenium are not unique to photovoltaics. The projected life time of the current estimated reserves of indium and selenium are to first order unchanged by the presence or absence of CIS PV production.

Current indium prices reflect the influence of supply and demand. Between late 1994 and mid-1995, average quoted indium prices roughly tripled in response to the cessation of material flows from the former Soviet Union, an increase in trader speculation, and stockpiling (largely in Japan) for use in indium tin oxide coatings for flat panel displays. Given the low fraction (e.g. 2.5 - 5%) of indium costs in the overall projected cost of a CIS PV module, it remains unlikely that indium prices will significantly impact the commercialization prospects of CIS PV technology or warrant indium-based materials recycling; but indium price increases could result in

Table 3. Module Material Resources

		CIS PV g/m² † MT/yr*	U.S. Use MT/yr	World Use MT/yr	World Resources MT	CIS PV Reserve GW	Primary Sources
Cu	=	1.6	2,300,000	9,000,000	2,000,000,000	10^8	Cu ores
In	=	2.3	30	125	2300 - 4600∇	**100 - 200**	Zn byproduct
Se	=	3.7	500	1800	130,000+	3000+	Cu anode slimes
Ga	=	0.5	8	35	1,000,000	200,000	Al and Zn byproduct
S	=	0.15	13,000	55,000	5,000,000	3,000,000	petroleum refining
Mo	=	10	15,000	100,000	12,000,000+	120,000	MoS_2 or Cu ores
Cd	=	0.2	4,000	20,000	6,000,000	3,000,000	Zn byproduct and EAF dusts
Zn	=	7	1,200,000	7,300,000	2,000,000,000	25,000,000	Zn ores
glass	=	10,000	18,000,000				silica, limestone and soda ash

† 1 μm Mo + 1.5 μm CIS + 0.05 μm CdS + 1.5 μm ZnO; Ga/In = 1/3; glass/glass package; 100% materials use efficiency.
* 100 MW/yr at 10% efficiency
∇ Up to 5000 MT reserve in Zn ores; perhaps 3X increase if include Cu, Pb and Sn ores.

investigations of alternatives to indium usage as typified by present materials and junction structure.

4 U. S. ENVIRONMENTAL REGULATIONS

Federal and State environmental regulations can have a significant impact on product manufacturing, use, and disposal and/or recycling. The focus of this work is on waste handling, disposal and recycling in manufacturing and at product end-of-life, thus the primary Federal regulation at issue is the Resource Conservation and Recovery Act (RCRA), its various amendments, and corollary State regulations.

RCRA relates only to solid wastes and defines a solid waste as any "discarded material" that is not specifically excluded. A discarded material is defined as anything being abandoned, recycled, or that is "inherently waste-like". Under RCRA, "abandoned" means disposed of, incinerated, or accumulated for disposal or incineration; and CIS PV modules would be considered solid wastes if abandoned. "Recycled" materials that are solid wastes include those recycled in a manner constituting disposal, burned for energy recovery, accumulated speculatively, reclaimed to recover a usable product, or regenerated. Materials are excluded from being considered a solid waste if they are used, reused or returned to the original formation process without being reclaimed (with some additional exceptions to this exclusion).

Neither PV in general nor CIS in particular are excluded (under 40 CFR 261.4) from the general definitions of a solid waste. CIS materials and CIS PV modules are not inherently waste-like per RCRA definitions, but end-of-life CIS PV modules will likely be solid wastes unless handled in a manner that qualifies for exclusion. As will be discussed in further detail below, un-used defective PV modules and various manufacturing byproducts (e.g. broken module plates, patterning dusts, etc.) might be exempted from being handled as a solid waste if sent for (certain types of) reclamation.

RCRA assigns a hazard classification to wastes based on four characteristics (Table 4). RCRA defines the Toxicity Characteristic Leaching Procedure (TCLP) test for quantifying the soluble, hence bioavailable, fraction of a solid waste. TCLP limits are defined for 39 organic and inorganic materials. A solid waste that yields a soluble concentration of these materials in excess of the TCLP limits for the specific materials is deemed to be a hazardous waste by way of exhibiting a hazardous characteristic of toxicity.

The California Hazardous Waste Control Law (HWCL) incorporates and expands upon RCRA. California law includes the same basic hazardous waste "characteristics" of ignitability, corrosivity, reactivity and toxicity; but California adds additional criteria to

Table 4. Federal and State of California Waste Classification

	Federal	California
Agency	Environmental Protection Agency	California Environmental Protection Agency Department of Toxic Substances Control
Law	RCRA and others	Hazardous Waste Control Law and others
Lists	40 CFR 261 - 268 lists F, K, P, U	CCR 22-66261, Apx. X presumptive hazard
Characteristics	1. Ignitability 2. Corrosivity a. liquid 3. Reactivity 4. Toxicity a. soluble concentration via TCLP 8 inorganics, 31 organics	1. Ignitability 2. Corrosivity a. liquid b. solid 3. Reactivity 4. Toxicity a. soluble concentration via WET 19 inorganics, 20 organics b. total concentration 20 inorganics, 18 organics c. acute toxicity oral, dermal and inhalation LD/C_{50} d. acute aquatic toxicity LC_{50} e. carcinogens < 0.001 wt% f. well-known hazard g. RCRA listed hazardous waste
Waste Categories	Hazardous waste Acute hazardous waste	RCRA and non-RCRA hazardous wastes Extremely hazardous waste Special waste

the corrosivity and toxicity characteristics, and defines wastes as RCRA (hazardous) wastes, non-RCRA (hazardous) wastes, extremely hazardous wastes, and special wastes. California law incorporates the RCRA TCLP test as part of its toxicity characteristic (to identify RCRA wastes) and adds the Waste Extraction Test (WET) to identify non-RCRA wastes that exhibit (California) toxicity characteristics. The WET test limits are given as the Soluble Threshold Limit Concentration (STLC), similar in may respects to the TCLP limits.

Of particular importance to CIS PV is the addition by California law of the total concentration criteria to the toxicity characteristic. The total concentration criteria seeks to quantify the total concentration of certain organic and inorganic materials in a solid waste. Total concentrations are determined by a strong acid extraction test and compared to the Total Threshold Limit Concentration (TTLC) limits. Roughly speaking, TTLC limits under California law relate to the total concentration of certain materials in solid wastes, and STLC limits relate to the soluble fraction of those total concentrations.

Under RCRA regulations (i.e. Federal law), CIS PV modules (not excluded from classification by the reclaim provisions of the solid waste definition) will likely be classified as non-hazardous provided the modules do not exhibit hazardous "characteristics", notably the toxicity characteristics of Subpart C, 40 CFR 261.24 (Table 5).

Table 5. Federal Waste Classification per RCRA

Hazardous if:	CIS PV Status:
1. Is a solid waste, AND	End-of-life modules likely are a solid waste
2. Isn't explicitly excluded; AND	Isn't excluded, unless is a household waste, e.g. 40 CFR 261.4(b) or by petition
3. Is "listed as inherently hazardous, OR	Isn't listed, e.g. lists F, K, P, and U in Subpart D
4. Exhibits hazardous "characteristics"	Doesn't, with some conditions, e.g. 261.24 Toxicity in Subpart C

Under HWCL regulations (i.e. California law), CIS PV modules (again only if not excluded from classification by the reclaim provisions of the solid waste definition) would likely be classified as non-hazardous if the TCLP and STLC tests were "passed", except that it is likely that current CIS PV structures will exceed the TTLC limits for total concentrations of selenium (Table 6).

Table 6. California Waste Classification

Hazardous if:	CIS PV Status:
1. Is a solid waste, AND	End-of-life modules likely solid waste
2. isn't explicitly excluded; AND	Isn't excluded [e.g. in CCR 22-66261.4]
3. is "listed" as inherently hazardous, OR	Isn't listed [e.g. CCR 22-66261.31 - 35]
4. exhibits hazardous "characteristics", OR	Exceeds TTLC for Se [e.g. CCR 22-66261.20 - 24]
5. contains anything presumed to be hazardous EXCEPT if not "listed" or is excluded under RCRA and doesn't exhibit hazardous characteristics OR	Contains many such things [e.g. "indium compounds" and exceeds TTLC for Se]
6. certain mixtures of hazardous materials, OR	Isn't such a mixture. [e.g. CCR 22-66261.3 (a)(2)(D) and (E)]
7. California EPA says so	Not to my knowledge [e.g. CCR 22-261.3 (a)(2)(F)]

A closer first-order examination of whether CIS PV modules will exhibit toxicity hazard characteristics under Federal RCRA or California HWCL can be obtained by calculating the total concentrations of various constituents and comparing these calculated concentrations to the TCLP, STLC and TTLC limits (Table 7). Assuming a junction structure typical of current CIS PV research devices and prototype products, one can calculate the concentrations of the constituents by weight relative to the total weight of the sample. Three cases were examined: an un-encapsulated plate of thin films on a single sheet of substrate glass, a glass/glass laminate with copper ribbons for electrical connections, and a framed module.

The calculated concentrations in a CIS PV plate, laminate and module were compared to the TCLP, TTLC and STLC limits of Federal and California law. All of the calculations assumed an ideal module without any stray materials, e.g. front-surface thin films due to physical vapor deposition "wrap around" or due to solution deposition processes. The TTLC comparison assumed that the TTLC extraction test completely dissolved all of the metals present. The TCLP and STLC comparisons assumed that all of the materials present were completely dissolved by the respective extraction tests, i.e. that all of the module materials were completely soluble in these weak acid extraction tests.

Table 7. CIS PV Module Leaching Determinations

2 mm glass / 1 μm Mo /1.5 μm CIS / 0.05 μm CdS / 1.5 μm ZnO / 0.5 mm EVA / 2 mm glass
Ga/In = 1/3 ; S/Se = 1/10 ; 240 cm PbSn-coated Cu ribbon per 0.5 m^2 module
ca. 1 kg anodized extruded Al frame per 0.5 m^2 module

	Plate	**Laminate**	**Module**	**EPA TCLP**	**1990 TCLP**	**1994 TCLP**	**California TTLC**	**California STLC**
	g/kg	g/kg	g/kg	g/kg soluble	g/kg soluble	g/kg soluble	g/kg	g/kg soluble
Cu film=	0.3	0.15	0.13				2.5	0.25
ribbon		1.9	1.6					
In =	0.5	0.22	0.18					
Se =	0.7	0.35	0.29	0.02	0.002	0.0012	0.1	0.01
Ga =	0.1	0.05	0.04					
S =	0.03	0.01	0.01					
Mo =	2	1	0.84				3.5	3.5
Cd =	0.04	0.02	0.02	0.02	0.003	0.0006	0.1	0.01
Zn =	1.4	0.7	0.59				5	2.5
glass =	995	955	801					
Pb =		0.2	0.17	0.1	0.08		1	0.05
EVA =		43	36					
frame =			160					

1990 TCLP tests by Asarco in cooperation with BNL; 1994 TCLP tests by Fraunhofer/GSF in cooperation with BNL
RCRA TCLP = Toxicity Characteristic Leaching Procedure
= 100 g/(20 x wt% solids x wt. of waste/100) = 100 g/2 L buffered acetic acid leaching solution ⇒ g/kg
= mg/L / 50
CCR Title 26: TTLC = Total Threshold Limit Concentration; STLC = Soluble Threshold Limit Concentration from Waste Extraction Test (WET); WET = 50 g sample / 500 mL 0.2 M sodium citrate extraction solution ⇒ g/kg
= mg/L / 100

Calculating the results under these assumptions, one would conclude that:

1. CIS PV plates might have marginally enough copper to exceed the STLC limits if all of the copper-containing materials are soluble in the WET test.

2. CIS PV plates, laminates and modules may have enough selenium to exceed the TCLP and STLC limits if more than a few percent of the selenium-containing materials are soluble in the TCLP or WET tests, and in any event have enough selenium to exceed the TTLC limits.

3. CIS PV plates, laminates and modules might have enough cadmium to exceed the TCLP and STLC limits if the cadmium-containing materials are soluble.

4. CIS laminates and modules might have enough lead (in Pb-Sn solder) to exceed TCLP and STLC limits if lead-containing solders are used and if the lead-containing materials are soluble.

Actual experimental data for the TCLP tests indicates that selenium, cadmium and lead are not dissolved in concentrations sufficient to exceed the TCLP limits. If the same is true of the STLC solubility tests, then CIS PV plates, laminates and modules would be expected to "pass" the TCLP and STLC criteria, but "fail" the TTLC criteria (for selenium). Thus, subject to certain conditions, one would expect CIS PV products to not exhibit any of the RCRA or HWCL characteristics of a hazardous waste except for exceeding the TTLC limit for the total concentration of selenium.

The general conditions under which CIS PV products would "pass" Federal RCRA toxicity characteristics are that the selenium-containing compounds aren't soluble, that the ideal assumptions of the calculated CIS junction structure are an accurate description of real devices (e.g. the CdS is thin and only on one side), and that the solder used to connect the ribbons to the Mo metal electrode is lead-free or skip soldered to assure that the Pb content is sufficient low (Table 8). The conditions under which CIS PV products would "pass" California HWCL toxicity characteristics are basically the same as for RCRA except that one must also address the Se TTLC issue.

There are three general pathways for obtaining a non-hazardous designation for CIS PV in spite of exceeding the TTLC limits for selenium (Table 9). First, one can seek changes to the underlying law through the California legislative process. Second, one can petition the California Environmental Protection Agency (Cal-EPA) Department of Toxic Substances Control to re-classify CIS PV as non-hazardous under provisions set forth in the HWCL. Such petitions require a filing fee of ca. $9000 exclusive of legal representation, typically require six months to process to completion, and generally result in a classification of one specific material from one specific generator (i.e. the

Table 8. Hazardous Waste Toxicity Determinations	
Under RCRA Characteristics	
TCLP indicates CIS PV is non-hazardous <u>if</u>:	**Se-containing compounds don't leach CdS is thin (e.g. <25 nm and on one side only) Pb-containing solder content is low**
Under California EPA Characteristics*	
a. soluble concentration:	in general requires same conditions as RCRA
b. total concentration:	exceeds TTLC for total selenium content, i.e. too much (insoluble) Se
c. acute toxicity:	oral, dermal and inhalation LD/C_{50} $\Rightarrow$ likely all pass, due to low concentrations e.g. oral LD_{50} < 5 g/kg: pure ZnO ~ 8 g/kg mouse, CdS ~ 7 g/kg rat and ~ 1 g/kg mouse
d. acute aquatic toxicity LC_{50} < 0.5 g/L $\Rightarrow$ likely pass	
e. carcinogens < 0.001 wt% $\Rightarrow$ contains none of the listed carcinogens $\Rightarrow$ pass	
f. well-known hazard $\Rightarrow$ no	
CIS PV is non-hazardous <u>if</u>:	**satisfy same conditions as with RCRA above, and obtain classification from California DHS in spite of TTLC characteristic**

* One can apply knowledge in lieu of analytical tests in making self classification of waste.

party in possession of the materials when they become a solid waste). It is unclear whether varying concentrations of CIS alloy materials such as gallium and sulfur would require separate petitions. A third option is to petition the Cal-EPA for a rule making change to its regulations. A rule making change can grant a generic exclusion for a given material (and perhaps for a family of materials) independent of the generator. A recent example of such a rule making change was the amendment of 26 CCR 22-66261.24(a)(2)(A) excluding MoS_2 from the TTLC determination. Petitions for re-classification and rule making must address specific criteria set forth by the

Table 9. California EPA Classification Options

1. Petition California EPA to reclassify CIS (PV) as non-hazardous

   Generally only granted for one specific material from one specific generator.

   Petition filing fee in California $9000 plus legal representation; 6 months for full process.

2. Petition California EPA for rule making change to regulations

   Can grant generic exclusion for a given material (or family of materials?) independent of generator [e.g. 1991 petition amended 26 CCR 22-66261.24(a)(2)(A) to exclude MoS_2 from the TTLC determination].

Reclassification and rule making requirements:

- Finding of insignificant potential hazard, [e.g. due to small quantity, low concentration or physical or chemical characteristics

- Petition must include:

  1. information on waste producer

  2. description of waste, including quantity, physical state, composition, source and production rate

  3. specification of variance wanted

  4. assessment of hazardous characteristics
     a. per lists, characteristics, etc.
     b. per Statement of Reasons 45-78 (if exceed TTLC)
        i. surface runoff and contamination of land and water
        ii. direct discharge to waterways
        iii. volatilization of organics
        iv. airborne dispersal before, during and after disposal
        v. direct on-site land contamination
        vi. long-term solubilization

  5. statement on how waste is to be managed

California EPA. No such petitions have yet been submitted for CIS PV materials, and it is not clear how the California EPA might respond to such a petition. RCRA contains additional provisions of key importance to determining how a material is to be handled. These provisions concern recycling, small quantity generators, household wastes, and when a product becomes a waste.

Solid wastes (other than sludges or those listed in 40 CFR 261 D) that are recycled are not subject to Subtitle C (i.e. the hazardous waste regulations of RCRA) under certain circumstances. Per 40 CFR 261.2(e), *recycled materials are not solid wastes* (ergo not hazardous wastes) if they:

1. are not being reclaimed and are used or re-used as an ingredient in a industrial process to make a product,

2. are not being reclaimed and are used or re-used as a safe and effective substitute for commercial products, or

3. are returned to the original process from which they were generated without first being reclaimed;

where in every case "reclaimed" means processed to recover a usable product. Section 261.4(a)(8) exempts secondary materials reclaimed and returned to the original process where generated. Section 40 CFR 261.6 contains language largely exempting scrap metal from Subtitle C.

The impact of these provisions of 40 CFR 261 is that used CIS PV modules could be handled as non-hazardous waste if sent for recycling as an ingredient in an industrial process or as a substitute for a commercial product. As will be discussed in further detail below, this allows used modules to be recycled by metal smelters who use the substrate and cover glass as sources of silica for their slagging material needs.

Under section 40 CFR 261.2(c)(3), certain materials are not solid wastes when reclaimed. Such exempted wastes include:

1. non-listed (i.e. in 40 CFR 261.31 & .32) sludges and byproducts (exhibiting a characteristic of a hazardous waste), and

2. commercial chemical products (listed in 40 CFR 261.33).

These exemptions under 261.2(c)(3) may allow various deposition and patterning debris and un-used defective modules to be handled as non-hazardous materials if recycled under exemptions 1 and 2, respectively.

Section 40 CFR 261.5 allows "small quantity generators" (i.e. less than 100 kg/month of waste) to treat their hazardous wastes at an on-site facility. This provision may allow small quantity generators to physically separate the metals-containing thin films from the (otherwise) benign glass substrates.

Section 40 CFR 261.4(b)(1) exempts all household wastes. This provision allows, for example, households to dispose of, say, an end-of-life PV-powered garden light, security system or residential PV power system as regular non-hazardous waste. If these products, however are burned in a municipal waste incinerator, the ash generated in the facility is not covered by this exemption, according to a recent Supreme Court decision (Supreme Court, 1994).

Inherent in all of RCRA is the need to determine when a product becomes a waste. Generally speaking a product becomes a waste (hence subject to RCRA) when one makes a reasonable determination that the product is spent and not usable for its intended purpose. In general this product-to-waste threshold is passed when it is not possible to refurbish a product for further use in its intended applications, whether by the original user or by a different user. For example, a used computer may be inoperable, but until it is reasonably determined to be beyond repair it is not a waste. Similarly, a used computer may be operable but obsolete to its original higher-level user, but may be in demand by a follow-on lower-level user. The product-to-waste transition occurs when the owner acts to dispose of the item, or when the manufacturer or refurbisher determines that the used item is not usable. Understanding the product-to-waste transition is essential to reasonably and legally handling used products as non-waste used products not subject to RCRA regulations until the products are determined to be a waste. As will be discussed in further detail below, this distinction is critical to the cost-effectiveness of collecting, consolidating, transporting and recycling used products.

California law has no corresponding exemptions for small quantity generators, or household wastes, or reclaimed byproducts and commercial products. In each case Cal-EPA classifies these wastes as non-RCRA wastes. However, California regulations do parallel 40 CFR 261.2 Federal regulations in exempting from classification as a solid waste those recycled (but not reclaimed) materials that are:

1. used or re-used as an ingredient in a industrial process to make a product,

2. used or re-used as a safe and effective substitute for commercial products, or

3. returned to the original process from which they were generated without first being reclaimed.

California regulations explicitly allow "pre-treatment" of wastes prior to use or re-use, provided that pre-treatment is limited to filtering, screening, sorting, sieving, grinding, physical or gravity separation, pH adjustment, or viscosity adjustment.

California regulations also parallel Federal in pertaining only to wastes and not to used products destined for further use.

Summarizing the present status of CIS PV products under existing Federal and California regulations (see also Table 10):

Table 10. Summary of EPA and California-EPA Regulations

Used end-of-life CIS PV modules

Unregulated non-hazardous trash if:

- Se-containing compounds don't leach,
- Cd is thin and on one side only,
- Pb-containing solder is used sparingly, and
- Cal-EPA grants exclusion or reclassification in spite of exceeding TTLC for Se

Likely exempt from hazardous waste regulations when recycled provided:

- Re-used as PV module (e.g. after refurbishing),
- Used as industrial process ingredient or substitute for commercial products, or
- EPA and Cal-EPA grant relief to facilitate recycling

Not a (Federal) hazardous waste if household waste

Un-used defective modules

Perhaps RCRA-exempt if send for reclaim as unlisted commercial chemical products

Likely can do in-house separation under EPA small quantity generator exemption, or as pre-treatment for reclaim

Various processing byproducts

Perhaps RCRA-exempt if send for reclaim as unlisted byproducts

- Used CIS modules :

  - will likely be unregulated non-hazardous trash if Cal-EPA grants an exclusion or reclassification for Se TTLC.

  - will likely be exempt from hazardous waste regulations when recycled, e.g. by a metals smelter.

  - may be able to undergo physical separation as pre-treatment for reclaim.

- Un-used defective CIS plates :

  - are likely exempt from RCRA regulation if reclaimed as an unlisted commercial chemical product.

    can probably undergo in-house physical separation as pre-treatment for reclaim.

- Various processing byproducts (e.g. flakes, dusts, etc.) are likely RCRA-exempt if reclaimed as unlisted byproducts.

The status of CIS PV products under Federal regulations may change if the EPA implements recommendations of the "Definition of Solid Waste Task Force" impaneled by EPA to recommend how RCRA could be improved to facilitate recycling (EPA-94). Among the Task Force's recommendations are simplification of the regulation of on-site recycling, captive recycling, product stewardship (i.e. recycling by returning to original manufacturer), and commercial (off-site) recycling. The Task Force also recommended language allowing "incidental processing" of materials to be recycled, in effect closely paralleling the existing California allowance of physical "pre-treatment" of materials to be recycled. If implemented, these changes would further simplify the collection, consolidation, transportation, and recycling of used PV modules.

5 LOGISTICS AND ECONOMICS OF CIS PV RECYCLING AND DISPOSAL

A recurring theme - whether considering material reserves, customer preferences or environmental regulations - is that materials recycling is potentially of importance to both the near-term and long-term commercial viability of CIS PV technology. But one must ask whether recycling is necessary or advisable given the realities of the marketplace (Table 11). Of particular importance are the logistics and economics of recycling.

The logistics and economics of CIS PV recycling and disposal were examined from three points of view. First, a zero-order estimate of recycling economics was made based solely on materials economics. Second, the prospects and pitfalls of recycling of similar products were examined by a survey of comparable industries. Third, regulatory framework, materials economics and the experiences of comparable

Table 11. Recycling - Is it Necessary or Advisable?

Materials Economics

Resource conservation for sustainability
Materials supply and demand
Waste disposal costs

Business Planning

Marketing competitive advantage, e.g. customer preferences and requirements
Liability, e.g. Superfund
Corporate culture

Laws and Regulations

Hazardous waste disposal, e.g. reverse retail collection and recycling of auto batteries
Waste disposal limitations, e.g. landfill conservation
Manufacturer take-back laws, e.g. packaging and containers in Germany

Recycling and Disposal Economics

Institutional infrastructure, e.g. collection, consolidation and transportation methodologies
Recycling, e.g. technologies, markets, regulatory framework
Disposal: handling and disposal costs
Economics: total cost/value including immediate costs and other business considerations

industries were synthesized into recommendations for a workable PV module recycling program.

5.1 Materials Economics

Barring credits for avoiding hazardous waste disposal costs or unusually high non-hazardous solid waste disposal costs, materials economics provide a zero-order estimate of recycling economics. As discussed above, materials account for 35 - 45% of total module manufacturing costs. From a typical module materials content and average source materials prices, one can calculate that the direct materials of a CIS PV module might cost the module manufacturer 20 - 25 ¢/W (Table 12). The reclaim value of module materials will be considerable less, due in part to the effective dilution of mixing the materials together as a PV module. From typical prices for

Table 12. Module Materials Reclaim Value

	g/m^2†	%wt.	$/m^2 new		$/m^2 end-of-life	
Cu in films	1.5	0.01	0.1	at $60 / kg	0.003	at $0.80/lb
in ribbon	20.	0.16	0.5	at 3 ¢ / ft	0.04	at $0.80/lb
In	2.5	0.02	1.0	at $435 / kg	0.25	at $100 / kg
Se	3.5	0.03	0.1	at $35 / kg	0.03	at $4/ lb
S	0.15	0.001	~ 0			
Ga	0.5	0.004	0.1	at $175 / kg	0.01	at $25 / kg
Mo	10.	0.08	0.5	at $50 / kg	0.02	at $2 / kg
Cd	0.2	0.002	~ 0			
Zn	7	0.06	0.2	at $25 / kg ZnO	0.004	at $0.25 / lb
glass	10,000	80.	10.	substrate and cover	0.055	at $5/ton
EVA	450	3.6	5.	extruded EVA sheet		
frame	2000	16.	10.	anodized extruded Al	1.55	at $0.35/lb

total : 28 $/m^2 = $0.23 / W at 10 % eff. = $2000 / ton — 2 $/m^2 = $0.02 / W at 10 % eff. = $140 / ton

Maximum End-of-Life CIS PV Module Value :
$115 / ton Al frame
$ 18 / ton In
$ 8 / ton other metals
$ 4 / ton glass

† Module structure: 2 mm glass/1 μm Mo/1.5 μm CIGS/0.05 μm CdS/1.5 μm ZnO/EVA/2 mm glass

comparable scrap materials, one can estimate the maximum likely materials reclaim value of a CIS PV module at 1 - 3 ¢/W. This reclaim value is dominated by the aluminum frame of a framed module and by the indium content of the CIS film (e.g., the Al frame and the indium in the CIS file account for 80% and 10-15% of the total reclaim value of a CIS PV module, respectively). If CIS technology follows the PV industry trend towards large unframed modules, then the reclaim value would be sharply reduced. Likewise, the indium value is likely difficult to realize in practice due to the dilution of the indium, even in the CIS film alone (e.g. 10 - 20 wt%), and to the aversion of indium refiners to indium materials containing copper.

Further insight into the potential materials reclaim economics of CIS PV modules can be gained by examining the primary and potential secondary sources of materials of importance to CIS PV technology (Table 13). In general, the concentration of materials in a CIS PV module are less than the typical concentrations in the primary and potential secondary source materials. The notable exceptions (e.g. In and Ga) are refined as byproducts from primary refining of other primary metals (e.g. Zn), hence their slight concentration advantages in a CIS PV module are unlikely to improve their reclaim economics. A possible exception to this general observation are the photoactive films themselves, but it is not likely that the additional reclaim value of the comparatively concentrated metals in the active thin films would offset the processing costs to separate the films from the glass and pottants.

Overall, materials economics suggest that it is unlikely that CIS PV modules can be economically recycled for their materials value. The highest salvage value of a CIS PV module is likely the silica content of the glass. Metals smelters who purchase silica for slagging use may be willing to recycle PV modules, though the sodium and calcium content of the glasses typically used in PV modules erodes the economic value as a slagging material.

5.2 Comparable Industries

Industries with comparable and/or complementary EH&S issues were examined with the aim of identifying benchmarks for CIS PV module disposal and/or recycling. Of particular interest were the electronics and telecommunications industries discussed by Reaven and by UNISUN (SUNY-94, SUNY-95, UNISUN-94).

To put the discussion of comparable industries in context, one can compare the average materials content of PV modules, electronic goods and appliances (Table 14). Thin-film CIS PV modules are dominated by their glass content, whether a double-pane framed structure (80 wt%), double-pane unframed structure (95 wt%), or a crystalline silicon style single-pane framed structure (65 wt%). In contrast printed circuit boards, computers, and telephones are dominated by metals, plastics and fiberglass. These differences in materials content can have an important impact on materials recycling techniques and economics.

Table 13. Primary and Secondary Materials Sources

		CIS PV module wt % †	CIS films wt%	Primary Sources wt %	Potential Secondary Sources
Cu	=	0.2 10		0.5 - 2 wt% in Cu ores	construction and electrical ; PC boards ; drosses, dusts, electroplating rinse slimes
In	=	0.02	13	up to 0.01 wt% in Zn ores	solders? used nuclear fuel rods?
Se	=	0.04	22	10 - 15 wt% in Cu slimes	photocopier old scrap
Ga	=	0.005	3	0.005 in Al and Zn ores	GaAs new scrap
S	=	0.002	1	petroleum refining byproduct	fossil fuel power plants?
Mo	=	0.10		MoS_2 or Cu ores	catalysts ; iron and steel
Cd	=	0.002	1	0.3 in Zn ores, 0.05 in EAF	NiCd batteries
Zn	=	0.07	40	50 wt% in conc. Zn ores	diecastings, brass, rolled items (e.g. gutters)
glass	=	99.6		silica, limestone, soda ash	container and plate cullet

† = 1 μm Mo + 1.5 μm CIS + 0.05 μm CdS + 1.5 μm ZnO; Ga/In = 1/3; S/Se = 1/10, 100% materials use efficiency
* = 10% efficiency

Table 14. Materials Content

	Weight Percent			
	glass	metal	plastic	other*
Framed, glass/glass PV module	79	18	3	0
Unframed, glass/glass PV module	93	3	4	0
Framed, glass/plastic PV module	65	30	5	0
Printed Circuit Board	0	32	0	68
Computer	15	42	22	21
Television Set	41	26	10	23
Telephone	0	8	69	23
Appliance	0	55	15	30

*e.g. cardboard and fiberglass

ref.: P.S. Dillon, IEEE Spectrum, August 1994, p. 18
M.B. Biddle & R. Mann, IEEE Spectrum, August 1994, p. 22

The printed circuit board industry is instructive from several points of view. A typical printed circuit (PC) board is 68% fiberglass, 30% copper and 2% PbSn solder (EPA-90). A PC board generally "fails" TCLP by a wide margin due to its lead content. However, by working closely with the EPA, the electronics industry has managed to get a number of important RCRA rulings facilitating board recycling. For example, per a May 1990 EPA memorandum, un-used defective boards are "secondary materials" which are un-listed (i.e. not listed in 40 CFR 261.33) commercial products which (per 40 CFR 261.2(c)(3) are not solid wastes when sent for reclamation (EPA-90). Per the same EPA memorandum, trimmings from board manufacturing are by-products which (per 40 CFR 261.2(c)(3) are not solid waste when sent for reclamation. Used boards are spent materials and would be solid wastes when reclaimed, except, per the EPA's 1992 Lowrance memorandum policy statement, spent PC boards are regulated by the EPA as scrap metal (which is exempt from Subtitle C regulation per 40 CFR 261.6(a)(3)(iv)) (EPA-92a). Processed boards (i.e. shredded, ground, burned, smelted, etc.) are generally considered to be spent materials, by-products or sludges, hence solid wastes; except some manufacturers (e.g. Apple Computer) have reportedly received EPA variances to retain scrap metal status in spite of cutting boards into 3 - 4 inch pieces to prevent unauthorized re-use. PbSn solder dross (i.e. oxidized skimmings from solder baths) are regulated by the EPA as by-product materials, hence (per 40 CFR 261.2(c)(3)) are not solid wastes when sent for reclamation (EPA-92b).

From the experiences and practices of the printed circuit board industry, one can conclude that un-used defective CIS PV plates and modules are likely "un-listed commercial chemical products" which are not solid wastes when sent for reclamation.

Similarly, one can conclude that debris and dusts generated during module manufacturing are likely "un-listed by-products" which are not solid wastes when reclaimed. Thus, provided a reasonably cost-effective reclaim procedure is available, CIS PV plates, modules and manufacturing by-products sent for reclaim likely do not require handling as hazardous wastes, independent of their TCLP test results.

The electronics and telecommunications industry recycles a wide range of used and unused products through a plethora of collection and processing channels. Used computers and telephones are typically collected, consolidated and shipped to a "service center". The used items are regarded as used products, not wastes, during these first steps in the recycling sequence, and as such no (hazardous) waste handling or processing permits and procedures are required. The service center does one of three things:

1. refurbishes the used equipment for resale as a working unit,

2. disassembles the unit for spare parts, or

3. dismantles the unit for materials reclaim.

Refurbished units and spare parts remain "products", while units and/or pieces sent for reclaim are "wastes" (subject to RCRA). The economics of electronics and telecommunications recycling is driven by the value of the usable components salvaged from recycled units and by the precious metals content of these items. Handling the incoming used items as "wastes" would impose significant additional (RCRA-related) costs and would undermine the economics of the overall recycling effort.

Paralleling these practices of the electronics and telecommunications industries, collection and consolidation of used PV modules (independent of materials content) would be greatly simplified if used modules were returned to the manufacturer or a contracted recycling center as "products" destined for (potential) refurbishment as PV modules. Since testing, evaluation and refurbishment would occur on (used) products (not wastes) and since simple pre-treatment (e.g. sorting, shredding, "physical" separation, etc.) is not waste "treatment" (in California and soon per RCRA revisions also), a manufacturer or refurbisher/dismantler could evaluate used modules for repair, disassembly or dismantling for reclaim without necessarily triggering "waste treatment" regulations.

The recycling programs of American Telephone and Telegraph Corporation (AT&T) are illustrative of how the telecommunications industry operates. Used products are gathered and shipped by independent contractors. Used products are sent to geographically dispersed re-use facilities (e.g. AT&T's facility in West Chicago) for refurbishment. Products not suitable for refurbishment are sent to dismantling centers where they are dismantled into usable spare parts, recyclable materials and wastes. One such center is AT&T's Materials Reclamation Center in Indianapolis, Indiana.

AT&T's Materials Reclamation Center (MRC) is permitted to handle "contaminated scrap" which would be hazardous (waste) if not recycled. MRC salvages usable components, then shreds and sorts the remainder for recyclable plastic and metal. Metal is typically sent to Noranda for recovery by smelting. PC boards are shredded and separated into metal and plastic streams. The PC board metal is then recycled as scrap metal (which when recycled is classified as non-hazardous by EPA). The PC board plastics are low enough in residual metals content to "pass" TCLP testing and be recycled as non-hazardous wastes. The overall reclaim value (of salvaged components and reclaimed materials) typically exceeds the costs of collecting, consolidating and transporting the used equipment to the reclamation center. As with other related products, the collection and physical dismantling of used telecommunications goods as "products", not (hazardous) "wastes" is essential to cost-effective recycling. The combination of a large and comparatively steady supply of used goods, relatively straight-forward physical disassembly and separation of the different reclaimable constituent materials, and substantial commercial value of the salvaged components and reclaimed materials make telecommunications recycling cost-effective for AT&T.

AT&T's MRC's processing capacity far exceeds its existing volume of AT&T equipment. AT&T is actively soliciting others with similar electronics scrap to participate in its recycling efforts. Unfortunately, the typical structure of CIS PV modules is significantly different from the typical goods recycled by the MRC, and it is unlikely that PV modules can be cost-effectively recycled through this channel.

Used goods can be collected through a variety of means. AT&T combines in-house collection with contracts with "reverse logistics companies". Reverse logistics companies provide collection, consolidation, pre-processing and transport services. AT&T contracts with Burnham Service Corporation and Equipment Recycling Services, among others.

Burnham Service Corporation retrieves, warehouses and transports materials from various generators (e.g. equipment owners, retail and wholesale distributors who accepted used equipment from original owners [e.g. in trade], municipalities [e.g. from community clean-up days], etc.) to reclaimers (e.g. re-use facilities and reclamation centers). Burnham will package and load used materials, transport the materials to a consolidation center for consolidation into 20 - 30,000 lb. full truck loads, and truck the materials to the reclaimer. Burnham has 28 branches nationwide and about 15 consolidation centers. Both non-hazardous (e.g. communications) and hazardous (e.g. batteries) materials are handled.

Equipment Recycling Services (ERS) also retrieves, warehouses and transports materials for recycling. ERS is an independently-owned affiliate of North American Van Lines (NAVL). ERS has a nationwide network of trucking affiliates and materials processors that it works with to move recyclable goods (e.g. via local trucking companies if a simple "common carry" pick-up of a banded pallet or box of materials, or via NAVL if special services and/or transport are required). Unlike Burnham which does not offer "break-down" services (e.g. pre-processing of collected goods), ERS offers a range of such services which might include, for example, removal of PV from a roof installation, or physical disassembly of modules (e.g. removable of frames) prior to transport to reclaimers.

Reverse logistics companies such as Burnham and ERS demonstrate that there are already in place nationwide collection, transportation and processing networks (for electronics and telecommunications equipment). However, given that photovoltaics markets are characterized by multitudinous small dispersed installations rather than a few large (utility) installations, a key first step to cost-effective collection by reverse logistics companies will be to effect some sort of initial concentration via reverse retail agreements, municipal solid waste recycling centers, etc.

AT&T's Materials Reclamation Center is operated for AT&T by an independent contractor. An alternative to manufacturers' in-house operations is independent recycling companies. Two such independent recyclers are Texas Recycling and Refining in Houston, TX and Envirocycle in Halstead, PA.

Texas Recycling and Refining (TRR) disassembles, dismantles and reclaims electronics goods from AT&T, Fluke, Tektronics and others. TRR is one of four authorized AT&T recyclers. TRR receives truckloads of electronic goods, including PC boards shipped as DOT class 55 scrap in open "Gaylord" cardboard containers, and solder dross and shredded PC boards shipped in sealed 55 gallon drums. TRR manually disassembles and sorts the incoming materials into various reclaimable materials streams. PC boards are sent to Noranda for smelting; other materials are process in-house or at other processors. Overall economics are dominated by precious metals value. A typical printed circuit board has a reclaim value of 50 - 75 ¢/lb.; 1980's boards have significantly more precious metals, hence a reclaim value of $1.50 - 1.75/lb. TRR is very interested in PV module recycling if workable disassembly methods could be identified.

Envirocycle disassembles, dismantles and reclaims a wide range of electronics and white goods (e.g. appliances). Envirocycle focuses on materials reclaim value, not salvageable components. They charge $6.25 - 8 per monitor to reclaim computer monitors. Monitor cathode ray tubes are separated into their three constituent glasses, and the (otherwise hazardous) leaded glass is sold at ca. $40/ton as crushed cullet to tube manufacturers for use in the 50% post-consumer cullet mix used to make new tubes. Envirocycle only takes items for which is has pre-identified direct outsources (i.e. other companies who will take the reclaimed materials), and they would likely be willing to recycle PV modules only if markets were clearly identified for all secondary (i.e. reclaimed) materials that would result. Envirocycle has had to negotiate simplified transportation regulations on a state-by-state basis, suggesting that some PV module recycling details (e.g. shipping requirements) may be complicated by a patchwork of state-by-state regulation.

In addition to the network of companies active in recycling electronics and telecommunications goods, there are other recycling efforts which face EH&S issues comparable to those of the PV industry. One such activity is the recycling of fluorescent light tubes. Fluorescent light tubes are similar to thin-film PV modules in being potentially classified under Federal and State regulations as "hazardous" due to metals-containing coatings on glass. For example, fluorescent light tubes have mercury in the phosphor powder on the inside of the tube, and fluorescent light tube disposal is strictly regulated (albeit at this time generally only for large generators). Tubes are recycled in one of two methods. In one method the tube is ground under vacuum, and the phosphor powder is collected in a baghouse and precipitator. In the second method, the phosphor powder is removed from an intact tube by a combination of gas pressure and vacuum. Collected powder is distilled in a retort to reclaim the mercury. The glass is sold as road bed material or as ground glass cullet for making fiberglass, glass bricks, etc. In California, fluorescent light tube pick-up and recycling costs the generator 7 - 10 ¢ per linear foot. California tube recyclers are narrowly permitted for tube processing and are not interested in recycling PV modules.

The experiences of fluorescent tube recycling in California demonstrate that the recycling of glass-containing products strongly depend on the ease of separation of any undesirable (e.g. Pb-containing phosphors) materials from the glass. In any event, markets for recycled glass are at present characterized by low prices, regional demand variations and tight glass cullet specifications.

Plate and container glass recycling likewise has some useful lessons but offers no clear pathway to profitable PV module recycling. Glass "beneficiation" (i.e. recycling) generally follows a logistics chain that begins with curbside pick-up by a hauler/recycler. The hauler/recycler typically transfers the materials to a processor who provides consolidation and paperwork services for the smaller recyclers. The processor transfers the materials to a beneficiator who crushes and cleans the glass to the manufacturer's cullet specifications. Recycled container glass cullet is typically sold to container manufacturers for re-use in 50/50 mixtures with virgin materials. Recycled plate glass cullet can be sold to plate glass manufacturers, but more often is sold to fiberglass manufacturers.

The key to glass recycling is the separation of glass, plastic, metal and paper. A wide variety of innovative processes and machines are used to do this separation.

Unfortunately, glass-containing products that are close corollaries to laminated PV modules are at present seldom cost-effective to recycle. For example, laminated front auto windshields are generally not recycled because the laminate plastic is difficult to remove and hinders the grinding of cullet to the manufacturer's specifications. Rear auto windshields are generally not recycled because the defogger wire exceeds the metal content limits of most glass manufacturers. Mirrors are generally landfilled in lieu of the effort and expense of removing the reflective metals.

PV modules will likely be difficult to recycle via glass recycling channels due to their metals content and difficulty in grinding the laminate to cullet specifications. If however a non-laminated PV module package were used (e.g. the glass/glass edge-sealed package being developed by Golden Photon), then it might be possible to separate the glass and films sufficiently to recycle the glass through existing glass recycling channels (and the films through existing metals recycling channels).

Materials separation and subsequent concentration are essential aspects of recycling. Another interesting example of this is the "aseptic" containers used for beverages (e.g. children's juice boxes). Aseptic containers are a layered structure of plastic, white paper board and aluminum metal. In the United States aseptic containers are recycled with paper milk cartons for their paper board value. In Europe aseptic containers are recycled for their metals value, though the original container is at most 6 wt% metal. By shredding and centrifuging it is possible to increase the metals content to ca. 25 wt%, sufficient for resale to metals recyclers. This suggests that the low metals content of CIS PV modules might still allow metals (and glass) recycling if the metal-containing materials can be separated from the glass. This also suggests that recycling value and strategy may vary with locale.

If PV modules are to be recycled it will likely involve primary and secondary metals companies. Metals companies generally are interested in high-concentration metals sources, quite unlike thin-film PV modules. For example, though indium suppliers do reclaim bulk indium and indium alloy materials (e.g. InSn and indium tin oxide sputter targets), they generally use these reclaimed materials only for less-demanding indium alloy applications, not direct re-use in, say, electronics. In particular low indium concentrations in CIS layers and the complicating presence of copper and selenium make it unlikely that indium suppliers will be interested in recycling CIS PV modules or CIS film materials.

Large primary and secondary metals smelters are able to cost-effectively process lower-concentration metals sources and are interested in working with PV module manufacturers to recycle thin-film PV modules. The Noranda Group in Canada recycles all manner of electronics and telecommunications goods, primarily for precious metals content. Noranda proposes to assist its high-purity materials customers in commercializing thin-film PV technology by offering low-cost PV module recycling services. Modules would be shipped to Noranda's copper smelters in

Canada where they would be used as a fluxing agent in lieu of the silica-bearing materials now used. The extraneous (metals) content of PV modules would likely not exceed the tolerance of the smelting operation for secondary materials.

Noranda has proposed a charge of $200/short ton, or $220/metric ton FOB the smelter for recycling thin-film PV modules, or roughly 2 - 3 ¢/W, exclusive of collection, consolidation, pre-processing and transportation charges. Noranda generally is not involved in the collection, consolidation, pre-processing and shipping of materials it recycles, but its recycling subsidiary in California - Micrometallics in San Jose - does provide such services to its electronics customers and might do so for the photovoltaics industry as well. Cross-country transportation might cost ca. 10 ¢/lb., equal to another 2 - 3¢/W.

5.3 Thoughts on Workable Recycling

A workable PV module recycling program will require careful attention to regulatory framework, materials economics, and the experiences of comparable industries. The basic viability of any recycling program often hinges on concentration of generators, processors, functions and content (Table 15).

Table 15. Recycling Viability Often Hinges on Concentration

- Geographic concentration of the goods and their proximity to appropriate recycling facilities
- Functional concentration in one entity or a small group of entities of the steps in recycling sequence, e.g. decommissioning, dismounting, collection, consolidation, pre-processing, transportation and recycling.
- Content concentration of valuable materials in the goods to be recycled

Thin-film photovoltaics is not at present very concentrated - by geography, by function, or by content. Present markets for PV are dominated by geographically dispersed installations such as off-grid power systems for industrial and stand-alone residential applications. Average PV system size is small compared to a minimum reclaim material transportation load accepted by smelters, e.g. 1 - 2 kW vs. 35 - 40 kW necessary to meet a 10,000 lb. minimum. Regulatory framework and legal liability concerns are likely to segment the PV module recycling sequence. Reclaimable materials content is low in total amount, low in concentration, and low in value. Materials reclaim value will likely be less than collection and processing costs. PV module recycling will at best be a challenge.

Reaven has proposed three generic institutional infrastructure paradigms to address the challenges inherent in recycling PV modules (Table 16 and ref. SUNY-95). In the "utilities" paradigm, large end-users (e.g. electric utilities) would be the primary owners and/or servicers of large (and/or large numbers of) PV systems, hence utilities would logically be primarily responsible for collecting and transporting end-of-life modules to recyclers. PV module recycling would be integrated with other utility programs such as conservation, off-grid service tariffs, demand side management, etc. Recycling charges would be imbedded in the rates charged by the utility.

Table 16. Generic Institutional Infrastructure Paradigms

I. Utilities

- Utility end-user primarily responsible for collection and hand-off to recycler.
- Recycling via utility collection, integrated dismantlers to sort and pre-process, and recyclers to reclaim materials.

ii. Electronics

- Module manufacturers individually responsible for collection and hand-off to recycler
- Recycling via reverse logistics companies to collect and transport, integrated dismantlers, and recyclers

iii. Batteries

- Module manufacturers collectively responsible for collection and hand-off to recycler
- Recycling via reverse retail chain and consolidation entities, dedicated dismantlers, and recyclers.

In the "electronics" paradigm, PV module recycling would mimic the recycling of electronics and telecommunications products. Module manufacturers would be (individually) responsible for collection and transport of end-of-life modules to recyclers. Collection, consolidation and transport would likely involve reverse logistics companies; and recycling would likely be done by integrated dismantlers (i.e. not exclusive to PV modules) and materials recyclers. Recycling services might be paid for by the generator, the manufacturer, or by some kind of escrow fund set aside at the time of PV system purchase.

In the "batteries" paradigm, module manufacturers would be collectively responsible for collection and transport to recyclers, probably through the incorporation of a collectively-supported independent PV module recycling entity similar to the

Rechargeable Battery Recycling Company set up by the Portable Rechargeable Battery Association. Collection, consolidation and transport would likely be done by reverse retail channels and consolidation entities; and recycling would likely be done by dedicated dismantlers (i.e. exclusive to PV modules) and materials recyclers. Goods collected through reverse retail channels could be transported directly to smelters via pre-paid shipping arrangements. Consolidation entities could collect goods from municipal recycling centers and large commercial and institutional generators. Recycling services might be paid for by industry dues to the collective recycling entity.

While these generic institutional infrastructure paradigms are useful in considering what elements of existing or potential recycling programs might be workable for PV module recycling, none of the paradigms is at present a good fit to the photovoltaics industry. For example, it is true that electric utilities are active in photovoltaics (e.g. on-grid and off-grid residential PV programs at Sacramento Municipal Utility District and Southern California Edison Company, respectively) and system owners have systematically dismantled and disposed of large PV systems (e.g. the Carissa Plains and Hysperia systems decommissioned by Carizzo Solar). But utilities are not at present large consumers of photovoltaic products, and their future roles are unclear as the American utility industry is restructured to accommodate more competition. In the face of increased market competition and impending deregulation, utilities have been exiting the conservation and demand side management activities that would have provided a natural synergy with PV system stewardship; and some utilities (e.g. Pacific Gas and Electric) have stated their intent to exit power generation and focus on services. The rise of distributed power generation installed, owned and operated by a variety of utility and no-utility entities leaves no single (PV system owner) entity as a natural recycling focus.

The "electronics" paradigm similarly faces some problems given the existing realities of thin-film photovoltaics. For example, while electronics and telecommunications recycling economics are driven by parts salvage, precious metals reclaim and liability concerns, it is unlikely that thin-film CIS PV technology will exhibit any of these in amounts sufficient to pay for recycling collection, consolidation, transportation and processing costs. Unlike electronics where disparities in product requirements in different markets (e.g. Pentium computers are increasingly in demand in the First World; "286" computers are at present suitable and in demand in the Third World) and rapid product lifecycles (i.e. product lifecycles determined by technology and market demand advances, not by product functional lifetimes), photovoltaics is characterized by slower improvement rates that generally do not obsolete existing installed systems to a degree sufficient to warrant pre-end-of-life decommissioning and resale. The result is that PV re-sale volume and value is low. With regards to disassembly and salvage, unlike electronics where component salvage and manual disassembly into major reclaimable materials streams is typical, PV modules have few easily-removed parts save for the mounting frame. It will be difficult for a PV module recycler to do the initial separation into major materials streams. With regards to incorporating PV module dismantling into the existing operations of integrated or dedicated dismantlers operated for and/or by other industries, it is likely that PV modules will be sufficiently different as to be unworkable in these recycling facilities.

The "batteries" paradigm has developed largely in response to potential regulatory threats to battery sales and recycling markets. Thin-film CIS PV modules are unlikely to face potential regulatory burdens (e.g. RCRA hazardous waste classification) that warrant recycling to avoid costly and cumbersome disposal. Unlike batteries, CIS PV module recycling benefits (e.g. materials reclaim value, liability reduction, marketing advantages, etc.) will not likely exceed recycling costs (e.g. collection and processing). Unlike batteries, the gross margins of PV module manufacturers are likely insufficient to fund recycling programs. Unlike batteries, the long functional service life of a PV system complicates the customer education needed to assure high return and recycling rates.

While none of the generic institutional infrastructure paradigms is at present a good fit to the photovoltaics industry, the paradigms are useful in identifying elements of existing or potential recycling programs that might be workable for PV module recycling. Four general observations can be made with respect to CIS PV module recycling (Table 17). First, paralleling the "utility" paradigm, the collection of decommissioned PV modules is probably feasible in the case of large, centralized installations. Collection might occur with the participation of the system owner, the module manufacturer, and/or the system installer. PV system installers will likely have the equipment and personnel necessary to decommission and break down PV systems provided the PV system components (e.g. the used modules) are not RCRA hazardous wastes. Given the concentration of modules in a large PV system, direct shipment of the used modules from the decommissioning site to the recycler (e.g. a smelter) is likely the lowest-cost strategy. The costs of recycling large systems can be absorbed by the system installer (and likely reflected in a higher initial system price) or capitalized by the system owner.

A second observation is that the collection of dispersed modules in small, remote and/or consumer applications will be problematic. Paralleling the "battery" paradigm, reverse retail channels and periodic pick-up by reverse logistics companies are likely the best strategy. Given the market segmentation and materials dispersion of PV products, collection action by PV module manufacturers is essential, but competitive pressures and lack of regulatory imperative reduce the prospects for the necessary collective action. An intermediate role for dismantlers may be warranted if only to remove the module mounting frame and junction box for separate recycling through scrap metal and plastics channels, respectively. Recycling costs of modules collected from dispersed sources might be borne by retailers and/or manufacturers.

A third observation is that the recycling of modules collected by municipal entities should likely be handled by the PV industry with an arms-length information role.

Table 17. Observations on Recycling of CIS PV Modules

1. Collection of decommissioned modules from large installations is feasible
   - System installer likely has equipment and personnel to decommission if not RCRA hazardous.
   - Direct shipment from decommissioning site to recycler likely lowest-cost strategy.
   - Recycling costs to be absorbed by system installer or capitalized by owner.

2. Collection of dispersed modules in small, remote and/or consumer applications is problematic
   - Reverse retail chain coupled with periodic pick-up by reverse logistics companies likely best strategy.
   - Collective action by PV module manufacturers is essential.
   - Intermediate role for dismantlers may be warranted, e.g. frame and junction box removal.
   - Recycling costs to be borne by retailers and/or manufacturers.

3. Recycling of modules collected by municipal entities are likely best handled with arms-length informational role by industry

4. Multi-material recyclers express guarded interest in recycling PV modules
   - Multi-materials recyclers have a wide spectrum of process expertise that might accommodate PV module recycling.

Municipalities may separate end-of-life PV modules from other municipal solid waste, particularly if the modules are classified as a hazardous waste under Federal, State or local regulations. The PV industry could provide guidance for municipalities (e.g. through the Solar Energy Industries Association) without assuming the legal liability of getting directly involved with the handling and recycling of these materials.

A fourth observation is that multi-materials recyclers such as those entities active in electronics and telecommunications equipment recycling may be useful participants in PV module recycling efforts even if PV modules fail to provide the component salvage and precious metals reclaim values that normally support recycling in those fields. These multi-materials recyclers have a wide spectrum of process expertise that might accommodate PV module recycling in the future. Recent discussions with representative entities in these fields indicated guarded interest in discussing this possibility.

The actual recycling of CIS PV modules will likely proceed along four technological steps (Table 18). The first step is simple disassembly to remove the mounting frame and junction box. Typical anodized aluminum mounting frames are recyclable through existing scrap metal channels. The junction box may be recyclable, but any event should be removed to facilitate high-density packing for shipment to the materials recycler. The second step is pre-processing that might include shredding and/or grinding to meet the incoming materials specifications of the recycler, e.g. a smelter. The third step is materials separation to the extent possible. It might be possible to separate the active layers from the package via mechanical, thermal or chemical means. The fourth step is materials recycling. If it is possible to break the module package and separate the constituent materials, then separate specific recycling of materials is possible. It is more likely that the materials will not be easily separable, thus mixed material reclaim (e.g. smelting, pyrolysis, incineration, molten metal baths, etc.) will be necessary.

Table 18. PV Module Recycling Technology

1. <u>Disassembly</u>

- If framed, then likely first remove frame for separate recycling
- If to go to smelter, then likely remove junction box, if any.
- If double-pane construction without pottant, then likely remove back sheet from PV module plate.

2. <u>Pre-Processing</u>

- If non-hazardous and if to go to smelter, then likely shred or grind.

3. <u>Materials Separation</u>

- If glass/PV/plastic film construction, then perhaps thermal decomposition, or solvent or acid dissolution of plastic, pottant, and , perhaps, PV layers.
- If unencapsulated substrate/PV plate, then mechanical, thermal or chemical removal of PV layers.
- If glass/PV/glass construction, then likely to remain as mixed-material waste, i.e. no materials separation. Perhaps possible to separate materials using mechanical, thermal, or chemical means; but it's tough.

4. <u>Recycling</u>

- If materials are separated, then recycle as appropriate for different materials.
- If materials not separated, then likely use mixed waste processes, e.g. smelting, pyrolysis, incineration, molten metal baths, etc.

The projected economics of recycling CIS PV modules can be estimated from the information gathered from comparable industries and existing recycling programs. Three cases were examined (Table 19). First, a base case assuming recycling of dispersed, low-concentration PV modules via reverse retail and/or curbside municipal solid waste channels was examined. In this base case an incentive paid to the generator and/or primary collector of $1/module might be necessary. Pick-up, consolidation and transportation to the recycler would be done by reverse logistics companies at ca. 10 ¢/lb. Recycling by a smelter might cost an equal amount. Frame removal and salvage might generate a slight profit. An administrative overhead of 10% would fund collective PV industry action such as educational action, administration of the incentive payments, etc. The net of this base case recycling scenario would be a recycling cost of about 8 ¢/W.

Table 19. CIS PV Recycling Economics

Base case recycling via reverse retail and/or curbside MSW	
- 2.5 ¢/W	incentive to generator and/or primary collector ; $1/module
+ 0.3 ¢/W	frame removal (-1.2 ¢/W @ 3 min, $10/hr) and salvage (+1.5 ¢/W @ $35/lb.)
- 2.3 ¢/W	pick-up, consolidation and shipping by Reverse Logistics Co. @ 10 ¢/lb.
- 2.3 ¢/W	pre-processing and smelting of laminates at $200/ton
- 1.0 ¢/W	administrative overhead for collective PV industry action; 10% out-of-pocket costs
0 ¢/W	NPV of future liability
- 8 ¢/W	paid by manufacturers
Best case recycling via reverse retail	
0 ¢/W	incentive to generator
0 ¢/W	incentive to retailer to take from generator and hold for pick-up
+ 0.3 ¢/W	frame removal and salvage
- 2.3 ¢/W	pick-up, consolidation and shipping by Reverse Logistics Co.; 10 ¢/lb.
- 2.3 ¢/W	smelting of laminates at $200/ton
- 0.5 ¢/W	administrative overhead for collective PV industry action; 10% out-of-pocket costs
+ 4.6 ¢/W	NPV of avoided future liability ; calc. as half present haz. landfill cost of $ 800/ton
+/- 0 ¢/W	cash flow by manufacturers
Generator-based recycling via direct transport to smelter	
0 ¢/W	incentive to generator and/or primary collector
- 6.8 ¢/W	direct transport to smelter in of framed modules in small quantities ; 25 ¢/lb.
- 4.6 ¢/W	pre-processing and smelting of laminates in small quantities at $400/ton
- 11 ¢/W	paid by generator

An alternate best-case recycling scenario would assume no incentive paid to the generator or primary collector and an Net Present Value activity credit of about 5 ¢/W for avoiding future environmental liability if disposed of instead of recycled. The net of this best-case recycling scenario is roughly break-even.

Generator-based recycling via direct transport by the small generator to the recycler would likely entail higher transportation costs (due to smaller shipment loads) and higher recycling costs (due to smaller processing loads). Large generators (e.g. utilities) would likely garner the lower rates possible with larger shipments and processing loads and be able to roughly balance recycling costs against future liability avoidance in order to achieve break-even.

6 CONCLUSIONS

Successful commercialization of CIS PV technology will require attention to environmental, health and safety issues, including source materials supplies and end-of-life products disposal and/or recycling.

Indium and selenium reserves will likely place an ultimate upper limit on the production of CIS PV products. This upper limit will be quite high - the same order of magnitude as the U.S. and worldwide electricity generation capacity in the cases of indium and selenium, respectively. Manufacturing process and device structure improvements can further extend these supplies. Though direct materials are a substantial fraction of the total projected manufacturing cost of thin-film CIS PV modules, it is unlikely that materials supplies alone will economically warrant end-of-module-life materials recovery.

PV modules and module manufacturing by-products and wastes are regulated under the Federal Resource Conservation and Recovery Act (RCRA) and under comparable State regulations. Under RCRA regulations, CIS PV modules (not excluded from classification by the reclaim provisions of the solid waste definition) will likely be classified as non-hazardous provided the modules do not exhibit hazardous "characteristics", notably the toxicity characteristics. The general conditions under which CIS PV products would likely not exhibit toxicity characteristics are that the selenium-containing compounds aren't soluble, that the ideal assumptions of the calculated CIS junction structure are an accurate description of real devices (e.g. the CdS is thin and only on one side), and that the solder used to connect the ribbons to the Mo metal electrode is lead-free or skip soldered to assure that the Pb content is sufficient low. Manufacturers of CIS PV products will need to design their products to meet these guidelines and closely monitor their production to assure that the guidelines are followed.

Under California regulations, CIS PV modules (again only if not excluded from classification by the reclaim provisions of the solid waste definition) would likely be classified as non-hazardous except for exceeding the Total Threshold Limit Concentration (TTLC) for selenium. The CIS PV industry can address the Se TTLC issue via legislative, re-classification, or rule-making processes. A collective effort by the PV industry to address this issue would be most effective.

Un-used defective CIS plates will likely be exempt from RCRA regulation if reclaimed as an unlisted commercial chemical product. Various processing byproducts (e.g. flakes, dusts, etc.) will likely be RCRA-exempt if reclaimed as unlisted byproducts.

Recycling economics for CIS PV materials will likely hinge on exemptions in Federal and California State regulations for solid wastes recycled as an ingredient in a industrial process, or as a safe and effective substitute for commercial products. In particular, metals smelters may use thin-film PV plates and modules as viable sources for silica content for slagging. Regulations allowing "pre-treatment" of wastes prior to use or re-use will be important in facilitating economic recycling.

Materials economics suggest that it is unlikely that CIS PV modules can be economically recycled for their materials value. The maximum likely materials reclaim value of a CIS PV module at 1 - 3 ¢/W. This reclaim value is dominated by the aluminum frame of a framed module and by the indium content of the CIS film. If CIS technology follows the PV industry trend towards large unframed modules, then the reclaim value would be sharply reduced. The concentration of materials in a CIS PV module are less than the typical concentrations in the primary and potential secondary source materials. The notable exceptions (e.g. In and Ga) are refined as byproducts from primary refining of other primary metals (e.g. Zn), hence their slight concentration advantages in a CIS PV module are unlikely to improve their reclaim economics. The highest salvage value of a CIS PV module will likely be the silica content of the glass for slagging use by metals smelters.

The experiences and practices of the printed circuit board industry suggest that un-used CIS PV plates, modules and manufacturing by-products sent for reclaim do not require handling as hazardous wastes, independent of their TCLP test results, if classified as "un-listed commercial chemical products" and/or "un-listed by-products" which are sent for reclamation.

Paralleling the practices of the electronics and telecommunications industries, collection and consolidation of used PV modules (independent of materials content) would be greatly simplified if used modules are returned to the manufacturer or a contracted recycling center as "products" destined for (potential) refurbishment as PV modules. A manufacturer or refurbisher/dismantler could evaluate used modules for repair, disassembly or dismantling for reclaim without necessarily triggering RCRA "waste treatment" regulations.

Reverse logistics companies are already in place providing nationwide collection, consolidation and transportation services to move recyclable goods from generators to recyclers. A key first step to cost-effective collection of PV modules by reverse logistics companies will be some sort of initial concentration via reverse retail agreements, municipal solid waste recycling centers, etc. Further discussions with representative reverse logistics companies could better quantify these requirements.

Materials separation and subsequent concentration are essential aspects of recycling. PV modules will likely be difficult to recycle via glass recycling channels due to their metals content and difficulty in grinding the laminate to cullet specifications. If however a non-laminated PV module package were used, then it might be possible to separate the glass and films sufficiently to recycle the glass through existing glass recycling channels and the films through existing metals recycling channels. Further work on PV module disassembly techniques will be important in quantifying whether modules can be cost-effectively disassembled for materials reclaim, or whether the focus must remain on recycling the unseparated module (e.g. shredded and fed into a metals smelter).

A workable PV module recycling program will require careful attention to regulatory framework, materials economics, and the experiences of comparable industries. Given the realities of materials recycling economics, PV module recycling will be a challenge.

Four general observations can be made with respect to CIS PV module recycling. First, the collection of decommissioned PV modules is probably feasible in the case of large, centralized installations. Collection might occur with the participation of the system owner, the module manufacturer, and/or the system installer. Second, the collection of dispersed modules in small, remote and/or consumer applications will be problematic. Reverse retail channels and periodic pick-up by reverse logistics companies are likely the best strategy. Third, the recycling of modules collected by municipal entities should likely be handled by the PV industry with an arms-length information role. Fourth, multi-materials recyclers such as those entities active in electronics and telecommunications equipment recycling may be useful participants in PV module recycling efforts even if PV modules fail to provide the component salvage and precious metals reclaim values that normally support recycling in those fields. Further discussions among PV manufacturers and between PV manufacturers and potential recycling participants would be helpful in better defining workable options.

The projected economics of recycling CIS PV modules estimated from the information gathered from comparable industries and existing recycling programs suggest a net cost of about 8 ¢/W for a base case assuming recycling of dispersed, low-concentration PV modules via reverse retail and/or curbside municipal solid waste channels; $1/module incentive paid to the generator and/or primary collector; pick-up, consolidation and transportation by reverse logistics companies at ca. 10 ¢/lb.; and recycling by a smelter at an equal cost; and an administrative overhead of 10% to fund collective PV industry action. An alternate best-case recycling scenario assuming no incentive and a credit of 5 ¢/W for avoiding future environmental liability yields a recycling cost of roughly break-even. A third case assuming generator-based recycling via direct transport by the small generator to the recycler would likely entail higher costs for small generators and lower costs for large generators. Further refinement of these cost estimates requires additional data from the potential participants. Clearly, given that the best case shows near break-even economics, module manufacturers should approach company-sponsored recycling programs with caution. Cost-effectiveness, liability moderation and regulatory constraints likely favor collective action by the PV industry as a whole.

7 RECOMMENDATIONS ON FUTURE WORK

This work focused on CIS materials. Future work providing a comparable examination of photovoltaic technologies based on crystalline silicon, amorphous silicon, and CdTe (e.g. examination of environmental regulations in the depth done here for CIS) is highly recommended.

This work focused on identifying potential processes and participants in disposing of and/or recycling (CIS) PV modules. Several of the potential participants are interested in receiving samples of CIS and CdTe PV modules in order to do scoping experiments and first-order economic analyses. A project aimed at providing the samples and analyzing the various results is recommended.

This work focused Noranda's preliminary proposals for recycling PV modules. Future work could include in-depth discussions with Noranda and other suitable metals companies (e.g. Asarco, Boliden, etc.).

This work focused on Federal and California environmental regulations. Further work could include other states of importance to present and future PV markets (e.g. Nevada, Idaho, New York, etc.).

This work combines UNISUN's expertise in photovoltaics materials and processes with its experience in environmental, safety and health issues. Further work combining the photovoltaics expertise of UNISUN and the broad materials recycling expertise of Reaven of SUNY-Stony Brook could generate new concepts for recycling PV modules.

This work focused on gathering and analyzing materials handling and recycling information of use to the PV community. In all probability dissemination of this information will be limited to published reports and conference poster presentations. Funding for expert participation in the tutorials to be given at the next IEEE

Photovoltaics Specialist Conference would assure a clear communication of the results of this and related work to the broad photovoltaics community.

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APPENDIX: LIST OF CONTACTS

Ms. Lieve Priano
Tetrapak (manufacturer of
Aseptic juice boxes)
Portland, OR
(503) 721-4200

Mercury Recovery Services (recycler
of fluorescent light tubes)
Monrovia, CA
(818) 303-2053

Jerry Balch
Lighting Resources Inc. (recycler of
fluorescent light tubes)
Phoenix, AZ
(800) 572-9253

Ron Stow
AT&T Corporate Environmental
Denver, CO
(303) 290-5255

Steve Bishop
AT&T Materials Reclamation Center
Indianapolis, IN
(317) 228-1520

Joel Danker
AT&T re-use center
W. Chicago, IL
(708) 876-1690

Burnham Service Corp.
5000-T Burnham Blvd.
P.O. Box 7966
Columbus, GA 31908
(706) 563-1120
contact on AT&T materials:
Gary Manning (?) at (800) 726-6046

Les Bury
Environmental Health & Safety
Customer Service
Equipment Recycling Services
2140 Professional Dr. #200
Roseville, CA 95661
(800) 258-0070

Michael Filandro
Texas Recycling and Refining, Inc.
1920 Rankin Road
Houston, TX 77073
(713) 443-2070

Ms. Tina Halley
Envirocycle
Hallstead, PA
(717) 879-2862, ext. 242

Don Cubbison
California Crinc
City of Commerce, CA
(213) 887-6158 (or -6150?)

Larry Annigoni
All Waste Recycling
Sacramento, CA
(916) 446-8994

Mike Senters
All Waste Recycling
Newark, CA
(510) 791-6985

Ms. Anne Kalajian
Gallo Glass
California
(209) 579-3411

Mr. André Amy
California Environmental
Protection Agency
Dept. of Toxic Substances Control
1011 N. Grandview Avenue
Glendale, CA 91201
(818) 551-2830

Knoll Laverty
California Environmental
Protection Agency
Dept. of Toxic Substances Control
Regulations Group
Sacramento, CA
(916) 255-3618

Mr. Terry Escarda
California Environmental
Protection Agency
Dept. of Toxic Substances Control
Pollution Prevention Group
Sacramento, CA
(916) 322-7287

Trevor O'Shanoughsey
California Integrated Waste
Management Board
Sacramento, CA
(916) 255-2624

Steve Storelli
California Integrated Waste
Management Board
Sacramento, CA
(916) 255-2470

Ms. Claudia Moore
California Environmental
Protection Agency
Dept. of Toxic Substances Control
Recycling Group
Sacramento, CA
(916) 322-4742
also : Norm Riley

Dr. James (Jim) Carlisle
California Environmental
Protection Agency
Dept. of Toxic Substances Control
Waste Evaluation Unit
Sacramento, CA
(916) 327-2506

Ms. Marianne Goode
U.S. Environmental Protection Agency
Regulatory Development Branch
Washington, D.C.
(202) 260-6299

Michael Benson
Noranda Advanced Materials
Pointe-Claire, Quebec
Canada
(514) 856-6956
FAX (514) 630-9379
point of contact for Noranda PV and
PV recycling activities

Barry Bailey
Noranda Sampling
East Providence, RI
(401) 438-9220
precious metals content sampling
of goods for recycling

Mr. Hai Teh
Vice President Operations
Micrometallics
San Jose, CA
(408) 998-4930
electronics recycling subsidiary
of Noranda

Paul Healey
Asst. Manager Recycling
Noranda Copper Concentrate
and Recycling
Toronto, Canada
(416) 982-7321

Brian O'Neill
Arconium
Newport Beach, CA
(714) 757-0111 ext. 525
thin film materials product line manager

Mark Chaganon
Metalspecialties, Inc.
Fairfield, CT
(203) 384-0335