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Health, Safety and Environmental Risks from the Operation of CdTe and CIS Thin-film Modules

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This paper identifies the materials embedded in one type of CIS (copper indium diselenide) and four different types of CdTe (cadmium telluride) thin-film modules. It refers to the results of our outdoor leaching experiments on photovoltaic (PV) samples broken into small fragments. Estimations for module accidents on the roof or in the garden of a residential house, e.g. leaching of hazardous materials into water or soil, are given. The outcomes of our estimations show some module materials released into water or soil during leaching accidents. In a worst-case scenario for CdTe modules the leached cadmium concentration in the collected water is estimated to be no higher than the German drinking water limit concentration. For the CIS module scenario the estimated leached element concentrations are about one to two orders of magnitude below the German drinking water limit concentration. For broken CIS and CdTe modules on the ground no critical increase of the natural element concentration is observed after leaching into the soil for 1 year. © 1998 John Wiley & Sons, Ltd.

INTRODUCTION

Large-scale and highly efficient CdTe and CIS modules consist of various active layers deposited on a substrate. The goal of a low-cost photovoltaic (PV) module operation demands optimized material selection to guarantee product quality and module stability on a long-term basis. In many PV applications the modules are exposed to extreme environmental conditions. Some modules are used under limited maintenance. Weather influences or human mishandling can cause technical defects of modules during operation. These problems are associated with material releases into the environment.

METHODOLOGY

The potential risks for the environment and health from thin-film modules may come from the release of hazardous substances, therefore we first identified the type and amount of chemical materials present in the investigated modules. By looking into the literature and interviewing the manufacturers, we derived the material selection and their mass contribution.

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The release of critical materials occurs only in the case of crushed or broken modules, when the rainwater can reach the active layers and leach out substances of the module fragments. In our outdoor experiments with broken modules we determined the leaching rate of module materials under normal PV operational conditions in the city of Munich, Germany. The experimental set-up comprised three boxes: one box with a module crushed into about 10 mm pieces, one box with an unbroken module and one box without any module as a blank. Rainfall could be collected in each box an drained into separate bottles for sampling. The eluates of these bottles were analysed weekly. All three boxes were oriented south and had a 48° tilt angle.

In a theoretical model together with experimental leaching data we considered a residential house with PV modules on the roof. The model has been split into two scenarios for the estimations with respect to concentrations in water and soil: the broken module remains on the roof; and the module falls down to the ground. The estimated concentrations of critical elements were then compared to (legislative and guideline) limit concentrations, if available, in order to assess potential risks for the environment and human health.

MATERIALS

Material content of the modules

Table I provides a survey of the type and quantity of materials contained in the modules and identified within the framework of this work. The values represent the amount of material present at operation of the thin-film modules. The weight of the glass substrate used for the deposition of the thin films varies between 4·7 and 12·4 kg m^{-2}. For the encapsulation materials (front and back cover of glass and/or metal, EVA sheet, aluminium or metal frame, insulation or adhesive material, electrical contacts, etc) a weight of 10 kg was determined for all four CdTe modules as well as for the CIS module. However, the shares of the encapsulation materials involved varied considerably. Module CdTe 3 is commercially available and uses rather thick CdTe and CdS layers due to the screen-printing technique.

SCENARIOS

Fracture of the modules and entry of substances into garden or household water

In principle, only substances in solution are biologically available and thus have a potential effect on humans. In this context, we observe the hypothetical case of a module fracture on the PV roof of a residential house, which is also used for collecting water for garden irrigation or household water.

Table I. Material content (in g m^{-2}) of thin-film modules[1]

	CdTe 1	CdTe 2	CdTe 3	CdTe 4	CIS
CdS	0·96	28·9	48·2	1·4	0·24
CdTe	12·4	37·2	62·0	15·5	–
Cd total	6·55	39·8	66·4	8·3	0·19
Te	6·6	19·8	33·0	8·3	–
Cu	–	–	–	–	1·95
In	–	–	–	–	3·75
Se	–	–	–	–	4·95
Mo	–	–	–	–	8·16
Zn	7	–	–	–	6·78
Glass substrate	4 960	7 400	4 660	12 400	4 960
Encapsulation material	10 000	10 000	10 000	10 000	10 000

Table II. Comparison of the element concentrations of the broken CIS and CdTe modules and the German regulations on drinking water

Element	Concentration in the outdoor test eluates	Concentration in the water collected from the roof	Limit concentration of the German drinking water regulation
CIS			
Zinc	2·1 mg l^{-1}	10·5 μg l^{-1}	5 mg l^{-1} (guideline)
Molybdenum	2·5 mg l^{-1}	12·5 μg l^{-1}	–
Selenium	0·4 mg l^{-1}	2 μg l^{-1}	10 μg l^{-1}
Cadmium	10 μg l^{-1}	50 ng l^{-1}	5 μg l^{-1}
Indium	30 μg l^{-1}	150 ng l^{-1}	–
CdTe			
Cadmium	1 mg l^{-1}	5 μg l^{-1}	5 μg l^{-1}
Tellurium	0·3 mg l^{-1}	1·5 μg l^{-1}	–
Nickel	0·1 mg l^{-1}	5 μg l^{-1}	50 μg l^{-1}

The following assumptions characterize the scenario:

(i) The broken module has an area of 0·5 m^2.
(ii) The total PV roof area is 100 m^2.
$\Rightarrow$The area ratio is 1/200.

The German regulation on drinking water[2] provides limit concentrations for elements in drinking or household water. Their purpose is to avoid any negative effects for humans, even under constant exposure. In the worst-case scenario one can assume that people drink water collected from the roof on a regular basis. Thus, the limit concentrations of the German drinking water regulation are suitable for comparison to the element concentration in the water collected from the roof under the above-mentioned assumptions.

Column 2 in Table II shows the concentration in the eluates from the outdoor test. Its element concentrations are taken from test conditions representing the most unfavourable case, i.e. a breaking of the module into relatively small fractions on purpose. The more common incident — a fracture due to stone impact or mechanical stress — will usually result in a much less extensive destruction of the module. Column 3 of Table II shows the element concentration in the roof-collected water. It corresponds to rain falling onto a roof of total area of 100 m^2 and washing out the contents of fragments of a 0·5 m^2 module. Column 4 represents the limit concentration of the German drinking water regulation.

For the CIS module type the zinc and cadmium concentration are approximately two and the selenium concentration one order of magnitude below the German drinking water limit concentration. The cadmium concentration of the CdTe module is in the regime of the German regulation. Generally, even in this worst-case scenario, only an insignificant danger for human health can be expected.

Fracture of the modules and entry of substances into soil

Due to a release of elements from the thin-film solar modules, critical substances may enter into soil as a consequence of washing out. As a comparison for the data gained in the outdoor tests with broken modules, here the Kloke list[3] is used (Table III). This list is a comprehensive collection of basic data on the total amounts of individual elements that can be tolerated. It was used as a fundamental guideline for the regulations on sewage plants[4] and a ruling of the State of Baden-Württemberg (Germany) on heavy-metal pollution on soil.[5]

This scenario is characterized by the following assumptions:

(i) The defect module remains on location in the garden for an entire year.

Table III. Broken CIS and CdTe modules: increase and natural concentration in soil–comparison to Kloke list[3]

Element	Increase of concentration in soil	Natural concentration in soil	Tolerable concentration (Kloke)
CIS			
Cadmium	83 μg kg^{-1}	0·1–1 mg kg^{-1}	3 mg kg^{-1}
Gallium	16 μg kg^{-1}	5×10^{-4}%[a]	10 mg kg^{-1}
Indium	20 μg kg^{-1}	10^{-45} mg kg^{-1}[a]	–
Copper	10 μg kg^{-1}	1–20 mg kg^{-1}	100 mg kg^{-1}
Molybdenum	2·2 mg kg^{-1}	0·5–5 mg kg^{-1}	5 mg kg^{-1}
Selenium	0·3 mg kg^{-1}	0·1–4·3 mg kg^{-1}	10 mg kg^{-1}
Zinc	2·2 mg kg^{-1}	3–50 mg kg^{-1}	300 mg kg^{-1}
CdTe			
Cadmium	240 μg kg^{-1}	0·1–1 mg kg^{-1}	3 mg kg^{-1}
Nickel	30 μg kg^{-1}	2–50 mg kg^{-1}	50 mg kg^{-1}
Tellurium	160 μg kg^{-1}	10 μg kg^{-1}[a]	–

[a]Abundance in the earth's crust.[7]

(ii) Leached substances distribute in the soil down to a depth of 25 cm over the module area.
(iii) The density of the soil amounts to 1·2 kg l^{-1} (according to Ref. 6, the soil densities range from 1·2 to 1·8 kg l^{-1}).

A comparison of the data demonstrates that in most cases the natural abundance of an element in the soil is increased only slightly due to eluates from broken solar modules. Moreover, for almost all elements the concentration in the soil remains below the tolerable concentration according to the Kloke list. Only for indium and tellurium is such a comparison not possible due to a lack of threshold values in the Kloke list.

CONCLUSIONS

During normal operation a release of critical elements into the environment and, finally, to humans can only occur as a consequence of accidents. Yet all investigated release scenarios, e.g. leaching of broken modules into garden water or into soil of a residential house, did not point towards an acute danger to human beings or the environment.

For a long-term bulk production, however, we have to expect a huge number of defect modules as a consequence of the end of the module lifetime. This corresponds to the amount of modules produced at the beginning of their lifetime. Thus module disposing in landfills is limited for two reasons: the loss of high-quality materials like metals or glass, the increasing leaching concentration of critical materials in the drain water of the landfill. This situation occurs when the volume concentration of dumped modules becomes higher than in the scenario of crushed modules on the ground. As a consequence, PV module recycling seems to be a major issue for future manufacturing and developing efforts.

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