Fate and Transport Evaluation of Potential Leaching and Fire Risks from CdTe PV

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ABSTRACT

Fate and transport analysis has been performed to evaluate potential exposures to cadmium (Cd) from cadmium telluride (CdTe) photovoltaics (PV) for non-routine circumstances (rainwater leaching from broken modules and emissions from fire). The analysis considers Cd transport from ground mount and roof mount systems via leaching, and from roof mount systems via fire and subsequent leaching. Fate and transport of Cd to soil from broken modules is based primarily on leachability, soil/soil-water partitioning coefficient, and annual rainfall. Subsequent migration to ambient air as windblown dust is dependent on both the particulate emission flux and on ambient air dispersion as modeled with a screening Gaussian plume dispersion model. Migration to groundwater is evaluated with a dilution-attenuation factor approach, and is dependent on leachability, infiltration rate, and source size. Fate and transport analysis of emissions from fire considers emissions to ambient air and transport to soil and groundwater from entrainment in water used to extinguish the fire. Fate and transport to air is dependent on the roof mount system size, Cd fire related emission rate, heat release rate, and ambient air dispersion as modeled with a screening Gaussian plume dispersion model. Fate and transport to water is dependent on the same factors that determine leaching to soil and groundwater described above. Using these modeling approaches, the relevant media-specific exposure point concentrations and/or daily intakes are estimated and compared to conservative health screening levels to evaluate potential health impacts to onsite and offsite receptors. It is concluded that potential exposures to Cd from rainwater leaching of broken modules and emissions from a fire are highly unlikely to pose a potential health risk to residents, workers, consumers, or emergency responders.

INTRODUCTION

Some stakeholders have raised concerns about the potential exposure to CdTe from leaching of broken modules and release during fires. Under normal operation, CdTe PV modules do not pose a threat to human health or the environment, as during the manufacturing process, the CdTe semiconductor layer is bound under high temperature to one sheet of glass, coated with an industrial laminate material, and then encapsulated between a second sheet of glass. However, questions may arise with regards to unusual events, namely broken modules subject to leaching by precipitation and modules exposed to fire.

Independent reviews carried out under the authority of the French, German, and Spanish governments [1-3] have concluded that emissions of Cd compounds are negligible under these non-routine circumstances. This analysis further extends these evaluations by using fate and transport modeling to estimate potential exposures to Cd compounds resulting from leaching and fire, and then evaluating the potential health effects associated with these exposures.

Broken modules refer to modules with cracked glass or broken pieces. Breakage results from extreme weather or human factors. While rare, breakage followed by precipitation may potentially result in leaching of CdTe from modules and subsequent exposure to Cd compounds in soil, air, or groundwater.

Modules can be exposed to building or grass fires affecting roof mount or ground mount systems, respectively. Under the high temperatures of a building fire (800 to 1100 deg C), the module glass fuses together with Cd diffusing into glass, limiting release. However, a small amount of Cd (0.04%) may be emitted before the two pieces of glass fuse together [4]. The effect of these emissions are considered for building residents, workers, and emergency responders.

For grass fires, flame residence times in grass fuels are approximately 15 seconds, and maximum temperatures are approximately 800 to 1000°C [5]. The melting point of CdTe is 1041°C, and evaporation begins at 1050°C [4], and the melting point of module glass is several hundred degrees centigrade higher. Therefore, for ground mount systems exposed to grass fires, Cd would remain encapsulated in the modules. Characterization of emissions from fire is an area of active research.

METHODS

Table 1 summarizes exposure scenarios evaluated with respect to rainwater leaching from broken modules and emissions from fire.

Leaching by Rainwater

Exposure pathways

For leaching from ground mount systems, potential receptors include installation/maintenance workers, commercial/industrial workers, and offsite residents. Installation/maintenance workers may be exposed via dermal contact with broken modules, and inhalation of windblown dust from affected soil. Commercial/industrial workers may be exposed via inhalation of, dermal contact with, and ingestion of Cd leached into soil, as well as exposure to groundwater potentially impacted by leachate. Offsite residents may be exposed to Cd via inhalation of windblown dust from affected soil, and exposure to groundwater potentially impacted by leachate.

For leaching from roof mount systems, potential receptors and exposure pathways are the same as for ground mount systems, except for the addition of onsite building residents, who also may be exposed to Cd via inhalation of, dermal contact with, and ingestion of Cd leached into soil, as well as exposure to groundwater potentially impacted by leachate. Additionally for roof mount systems, an exposure scenario considers a farm, with an array of modules on a building rooftop that uses collected rainwater to raise crops and cattle. The farm worker has the same exposure scenarios as the building resident, and an offsite consumer may be exposed through ingestion of farm beef, dairy products, and produce.

Table 1. Potential exposure scenarios associated with leaching from broken modules and emissions from a fire for CdTe PV

Scenario		Exposure Medium	Receptor
Leaching from Broken Module	Ground mount PV	Air, Module Contact	Installation/ Maintenance Worker
		Air, Groundwater	Offsite Resident
		Air, Soil, Groundwater	Commercial/Industrial worker
	Roof mount PV	Air, Module Contact	Installation/ Maintenance Worker
		Air, Groundwater	Offsite Resident
		Air, Soil, Groundwater	Building Resident, Commercial/Industrial Worker, Onsite Farm Worker
		Beef/dairy/produce	Beef/dairy/produce Consumer
Fire	Roof mount PV	Air	Emergency Responder
		Air, Soil, Groundwater	Building Resident/ Worker
		Air, Groundwater	Offsite Resident

Release mechanism

The concentration of Cd in leachate resulting from rainwater that falls upon and runs off broken modules is estimated based on a worst-case mass balance approach, where all the mass of Cd in each broken module is assumed to be transferred from the module into the volume of rainfall that falls upon the module during the exposure period. This mass balance-derived value is compared to laboratory measurement of the Soluble Threshold Limit Concentration (STLC) [6], which represents an upper end leachable concentration. The lower of these values is used as an upper bound of the potential leachate concentration. The concentration of Cd in rainwater runoff from the overall module array, which contains mostly unbroken modules, is calculated using a weighted average.

Transport to soil

The potential transport of Cd to soil is evaluated in accordance with the equilibrium-partitioning approach described in the USEPA soil screening guidance [7-8]. It is conservatively assumed that the surface soil where rainwater runoff is discharged is instantaneously impacted with Cd, at the concentration predicted by equilibrium partitioning between the water and soil matrices, as expressed by the soil/soil-water partitioning coefficient (K_d) value for Cd (Eq. 1).

$$CS_{eq} = CV \times \left(K_d + \frac{\theta_w}{\rho_b} \right) \qquad (1)$$

where:

CS_{eq} = equilibrium concentration of Cd in soil (mg/kg);

CV = concentration of Cd in vadose zone soil pore water (mg/L);

K_d = soil/soil-water partitioning coefficient (L/kg);

θ_w = soil water-filled porosity (unitless); and

ρ_b = soil dry bulk density (g/cm^3).

In the ground-mount system scenario, it is assumed that the rainwater that falls upon each module runs off the module onto an area of ground surface equal to the module area (i.e., 0.72 m^2). This situation is unlike the roof-mount system where impacted water is discharged to the same ground surface over and over again via gutter downspouts or collection and irrigation systems. In the ground-mount scenario, rather, the discharge of impacted water occurs at various locations over time as individual modules break at those locations. Over time, clean rainfall incident upon impacted soil will provide dilution of the Cd that was previously discharged to vadose pore water and soil from broken modules at those locations.

Transport to air

The potential transport of Cd from impacted soil to ambient air is estimated by: 1) assuming the USEPA-recommended default windblown dust emissions flux; 2) assuming that Cd is present in this windblown dust at the soil concentration predicted by equilibrium partitioning (described in previous paragraph); and 3) using the USEPA Gaussian plume dispersion model SCREEN3 [9] to estimate worst-case concentrations of dust, and thus Cd, in ambient air.

Transport to groundwater

The potential transport of Cd to groundwater is evaluated in accordance with the dilution-attenuation factor (DAF) approach described in the USEPA soil screening guidance [7-8]. It is conservatively assumed that vadose (unsaturated) zone soil water, from the ground surface to the groundwater table, contains Cd at the module array-runoff concentration discussed above (*i.e.,* it is assumed the soil column does not adsorb any Cd). An appropriate DAF is selected from the USEPA guidance, based on the source area. The potential concentration of Cd in groundwater at the hypothetical point of usage, which is assumed to be a groundwater extraction well located 25 feet from the edge of the source area, is calculated by applying the DAF to the vadose soil water concentration.

Plant and animal uptake

Product-related Cd present in rainwater runoff that is collected and used to irrigate crops and to feed cattle may potentially be transferred to plant and animal products and ultimately consumed by human populations. Potential plant and animal uptake of product-related Cd is modeled in accordance with Cal/EPA Hot Spots risk assessment guidance [9].

The concentration of Cd in vegetation grown onsite is estimated with a chemical-specific uptake factor that is a function of the vegetation type (exposed, protected, root, or leafy). Cd concentrations in beef and dairy products are a function of intake via dust inhalation, water ingestion, pasture ingestion, feed ingestion, and soil ingestion. The combined intake is subject to a chemical-specific transfer coefficient for the given animal product (i.e., beef or dairy).

Exposure assessment

Daily Cd intakes for potential receptors are calculated in accordance with standard USEPA and Cal/EPA exposure assessment methodology [9-13], using standard default Cal/EPA Office of Hazard Assessment Health (OEHHA) and Department of Toxic Substances Control (DTSC) exposure assumptions, and based on the exposure point concentrations developed through fate and transport modeling. Because it is not possible for both soil and groundwater to experience worst-case impacts, as quantified in this evaluation, soil- and groundwater-based intakes for the same receptor population are not summed, but rather are evaluated against health criteria separately.

Fire

Exposure pathways

For building fires affecting roof mount systems, potential receptors include building occupants (either residents or workers), offsite residents, and emergency responders (e.g., firefighters; see Table 1). Receptors may be exposed to Cd by direct inhalation of particulate matter associated with the smoke plume. In addition, building occupants and offsite residents may be exposed to Cd by contact with affected soil and groundwater (used as tap water).

Release mechanism

The release efficiency of Cd from modules in a fire (0.04%) is based on experimental studies in which samples of module were subjected to simulated fire events [2]. The total mass of Cd released from a module array during a fire is estimated from the number of modules in the array (i.e., the total mass of Cd available) and the experimentally measured release efficiency. All of the Cd released during the fire is conservatively assumed to be emitted over a period of time equal to the assumed exposure duration, which varies from 10 minutes to 8 hours based on the threshold exposure limit of comparison.

Transport to ambient air

The concentrations of Cd in ambient air, resulting from release from modules during a building fire, are estimated using the SCREEN3 Gaussian plume dispersion model [14]. Overall, the modeling approach is designed to quantify worst-case potential impacts at any receptor location downwind from the edge of the burning building and at any receptor height above ground surface, across a range of potential fire scenarios. All relevant regulatory model options (e.g., building downwash and fumigation) are employed (Table 2). USEPA-published persistence factors are applied to the worst-case 1-hour modeled concentration, to estimate worst-case concentrations over time periods of interest from an exposure perspective, ranging from 10 minutes to 8 hours.

Table 2. SCREEN3 Dispersion Model Input Parameters

Input Parameters	Unit	Small Building Fire	Medium Building Fire	Large Building Fire
Source Type	–	F (flare)	F (flare)	F (flare)
Flare stack height	m	5	5	5
Total heat release rate	cal/s	1.20E+06	2.99E+07	1.20E+08
Receptor height above ground	m	55	165	180
Urban/rural option	–	R (rural)	R (rural)	R (rural)
Consider building downwash?	–	Y (yes)	Y (yes)	Y (yes)
- Building height	m	4	4	4
- Minimum horizontal building dimension	m	10	50	100
- Maximum horizontal building dimension	m	10	50	100
Choice of meteorology	–	1 (full)	1 (full)	1 (full)
Automated distance array?	–	Y (yes)	Y (yes)	Y (yes)
- Minimum distance	m	5	25	50
- Maximum distance	m	1000	1000	1000
Fumigation calculation?	–	NA	Y (yes)	Y (yes)
Consider shoreline fumigation?	–	NA	Y (yes)	Y (yes)
- Distance to shoreline	m	NA	7.60E+02	1.98E+03

Transport to soil and groundwater

During a fire, particulates containing Cd may settle-out from the smoke plume and deposit to the ground surface, potentially resulting in Cd impacts to soil and ultimately to groundwater. Runoff of water used to extinguish the fire may also result in Cd impacts to soil and groundwater, if the Cd released from the modules were to be entrained in the fire water and discharged to the ground surface, instead of being entrained in the smoke plume and transported downwind. The wet deposition scenario (Eq. 2) is quantitatively evaluated here, as this scenario is protective of the dry deposition scenario. The evaluation of potential transport to soil and groundwater, in the context of wet deposition via firewater, is based on the same methodologies and assumptions made in the transport evaluation conducted for the leaching via rainwater scenario, discussed above.

$$C_W = \frac{M_{Cd}}{V_F + V_P} \tag{2}$$

where:

C_W = annual-average concentration of Cd in vadose soil pore water (mg/L);

M_{Cd} = mass of Cd released from modules in fire (mg);

V_F = volume of water used to extinguish fire (L); and

V_P = volume of annual precipitation that falls upon site (L).

RESULTS AND DISCUSSION

Rainwater leaching risks

Risks to workers, residents, and consumers with respect to rainwater leaching from broken modules are evaluated by comparing estimated daily intake (µg/day) to conservative screening levels with respect to inhalation cancer risk (10^{-5} threshold) and reproductive/developmental toxicity from oral exposure [15]. Note that because the dermal exposure pathway is either incomplete, lacking a screening level, or insignificant compared to the ingestion pathway, it is not discussed further.

Figure 1 summarizes health risks from rainwater leaching from broken modules. For each scenario, media-specific daily intakes are below screening levels. For inhalation exposures, estimated daily intakes are largely greater than 2 orders of magnitude below screening levels. For oral exposures, estimated daily intakes are largely greater than 1 order of magnitude below screening levels.

For the commercial office building and solar farm scenarios, estimated daily intake from oral exposure to groundwater is within an order of magnitude but below screening levels. Soil and groundwater impacts are based on the assumption of equilibrium partitioning between vadose zone soil water and soil. The equilibrium concentration represents the theoretical maximum concentration possible in the solid phase, for a given concentration in soil pore water.

This assumption is highly conservative because it does not account for the loss of chemical mass from the pore water, but instead assumes that the pore water constitutes an infinite source of chemical available for partitioning to the solid soil phase. In actuality, there is only a finite mass of chemical available (i.e., the mass that is released from broken modules), and as some of this mass partitions into the solid soil phase, the concentration in the pore water would decrease. Accounting for the loss of chemical mass from the pore water to the solid phase would lower chemical concentrations in soil water that are assumed to penetrate to groundwater and so reduce predicted groundwater exposures. Accordingly, impacts to groundwater are likely overestimated.

In addition for the solar farm scenario, estimated daily intake from oral exposure of groundwater is conservative based on assuming that the groundwater extraction well is located 25 feet away from the edge of the source. In this scenario, the potential sources of groundwater impact are the individual broken modules scattered across a 6,000-acre site. Therefore, the actual distance from impacted vadose zone soil water to the offsite groundwater extraction well would be much greater than assumed here for all broken modules except those adjacent to the site boundary.

Furthermore, it is assumed that the Cd released from every broken module at the site is transported to the same offsite groundwater extraction well. In reality, it is highly likely that only a fraction of the site would be within the capture zone of the offsite extraction well.

Another primary source of uncertainty in this evaluation is the estimation of Cd concentrations in module rainwater leachate, which is conservatively bounded by the results of laboratory STLC testing. These extraction tests were conducted on homogenized samples of finely crushed module, agitated over a 48-hour period in an acidic solution. This testing in no way mimics actual broken or cracked module exposure to rainwater because the STLC extraction provides a much longer contact time and larger surface area for contact (because the module is crushed first) than the module would experience during use.

Fire risks

Inhalation risks to workers, residents, and emergency responders with respect to fire are evaluated by comparing exposure point concentrations from the fate and transport analysis against acute exposure guidelines (AEGLs) [16]. The AEGLs represent threshold exposure limits for the general public and are applicable to emergency exposure periods ranging from 10 minutes to 8 hours.

Figure 1. Comparison of Estimated Daily Intake to Screening Values for Rainwater Leaching Scenarios

	Inhalation Exposures^{a}	Oral Exposures^{b}
INSTALLATION AND MAINTENANCE SCENARIO		
Installation and Maintenance Workers	●	-
RESIDENTIAL BUILDING SCENARIO		
Onsite Residents – Soil Exposures	●	●
Onsite Residents – Groundwater Exposures	●	◍
COMMERCIAL OFFICE BUILDING SCENARIO		
Onsite Commercial/Industrial Workers	●	●
Offsite Residents – Soil Exposures	●	-
Offsite Residents – Groundwater Exposures	●	○
BEEF/DAIRY/PRODUCE FARM SCENARIO		
Onsite Farm Workers	●	●
Offsite Residents – Soil Exposures	●	-
Offsite Residents – Groundwater Exposures	●	◍
Beef/Dairy/Produce Consumers	-	◍
SOLAR FARM SCENARIO		
Onsite Commercial/Industrial Workers	●	◍
Offsite Residents – Soil Exposures	◍	-
Offsite Residents – Groundwater Exposures	●	○

Notes:

a - From dust or aerosol tap water (showering) inhalation .

b - From soil, drinking water, or beef/dairy/produce ingestion.

● Ratio of Daily Cd Intake to Screening Value: <0.01

◍ Ratio of Daily Cd Intake to Screening Value: 0.01 - <0.1

○ Ratio of Daily Cd Intake to Screening Value: 0.1 - <1

For exposure to affected soil and groundwater in the fire scenario, risk-based screening levels of Cd in soil are based on potential exposures via soil ingestion, soil dermal contact, and dust inhalation. Risk-based screening levels of Cd in groundwater are based on potential exposures via drinking water ingestion, dermal contact with tap water while showering, and inhalation of tap water aerosols while showering.

Table 3 summarizes health risks from fire emissions. For each scenario, all estimated exposure concentrations are below conservative screening values, generally by one to two orders of magnitude. Exposure point concentrations are slightly higher for smaller building sizes than larger, due to lower heat release rate which produces less atmospheric dispersion than for large buildings.

Incremental cancer risks associated with short-term exposure to Cd were also evaluated in accordance with USEPA inhalation risk assessment methodology [13]. Estimated cancer risks were over an order of magnitude below the 1 in 1 million level considered by USEPA to be an insignificant risk.

For fire risk, a source of uncertainty is the use of the SCREEN3 Gaussian plume dispersion model for fire emissions. USEPA guidance notes that modeling a fire as a flare point source is conservative, as this assumption neglects the initial dilution provided by air which is drawn

Table 3. Comparison of Cd Exposure Point Concentrations to Health Screening Values for Fire Exposure Scenario

	Small building		Medium building		Large building	
	Exposure Point Concentration	Screening value^{a,b}	Exposure Point Concentration	Screening value^{a,b}	Exposure Point Concentration	Screening value^{a,b}
Ambient Air Evaluation (μg/m3)						
10 minute Averaging Period	26	130	25	130	23	130
30 minute Averaging Period	6.0	130	5.9	130	5.4	130
60 minute Averaging Period	3.0	100	2.9	100	2.7	100
240 minute Averaging Period	0.67	63	0.66	63	0.61	63
480 minute Averaging Period	0.26	41	0.26	41	0.24	41
Soil Evaluation (mg/kg)	0.42	39	2.80	505	3.40	505
Groundwater Evaluation^{c} (mg/L)	0.00002	0.0078	0.0004	0.0078	0.0011	0.0078

Notes:

(a) For ambient air evaluation, screening value is AEGL-1, the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic, non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure. There are three AEGL levels (AEGL-1, AEGL-2, and AEGL-3) distinguished by varying levels of toxic effects, with AEGL-1 levels as most stringent.

(b) For soil and groundwater evaluations, screening values are risk based screening levels (RBSLs) corresponding to cancer risk of 10^{-6} or hazard quotient of 1.

(c) For reference, California and U.S. Federal Maximum Concentration Limit (MCL) for Cd in water is 0.005 mg/L.

in over an area wide fire source. However, SCREEN3 is not specifically designed to simulate fires and so uses relatively simple correlations to describe the smoke plume.

To evaluate uncertainty, a large outdoor fire plume trajectory model - flat terrain (ALOFT FT) model [17] was run with inputs from the worst-case SCREEN3 modeling run (i.e., small building scenario). Overall, the SCREEN3 maximum concentration was higher than the ALOFT-FT maximum concentration. Therefore, these results further confirm that use of SCREEN3 to evaluate impacts associated with releases from fires is conservative.

SUMMARY AND CONCLUSIONS

Under normal operation, CdTe PV modules do not pose a threat to human health or the environment, because the CdTe semiconductor layer is encapsulated within the module. However, questions may arise with regards to broken modules subject to leaching by precipitation and modules exposed to fire. Conservative fate and transport analysis shows that potential exposures to Cd from rainwater leaching of broken modules or emissions during a building fire are highly unlikely to pose a potential health risk to residents, workers, consumers, or emergency responders. For modeled fire scenarios, exposure point concentrations are generally one to two orders of magnitude below conservative screening values, and estimated cancer risks are over an order of magnitude below the 1 in 1 million level. For each rainwater leaching scenario modeled, estimated health risks are below conservative screening values.

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