Designation: E3325 – 21

An American National Standard

Standard Practice for Sampling of Solar Photovoltaic Modules for Toxicity Testing[1]

This standard is issued under the fixed designation E3325; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 The purpose of this practice is to describe a representative and repeatable sample preparation methodology to conduct toxicity testing on solar photovoltaic (PV) modules for use with EPA Test Method 1311: Toxicity Characteristic Leaching Procedure (TCLP).

1.2 This practice refers to the extraction and preparation of PV module samples by EPA Method 1311, the testing for eight (8) distinct metals – mercury (by Method 7470A), arsenic, barium, cadmium, chromium, lead, selenium and silver (by Method 6010C) as well as the analysis and interpretation of the test results on a module level.

1.3 This practice applies to only *(1)* standard crystalline silicon (c-Si) modules, multi and mono-crystalline silicon with aluminum back surface field (Al-BSF) cell technology and *(2)* cadmium telluride (CdTe) PV modules.

1.4 Other and newer PV technologies and module architectures, for example, passivated emitter and rear cell (PERC), interdigitated back contact (IBC), hetero-junction technology (HJT), multiwire, half cut, shingled etc., have not been evaluated with this practice, although the concept and practice can be easily extended and applied to other technologies following the conceptual approach presented in this document.

1.5 The sample extraction/removal methodology applied in this practice is the waterjet cutting sampling method. Sample extraction with mechanical cutting has been extensively evaluated but the variability of TCLP test results based on the mechanical cut samples tend to be much higher (30 %) than that of the waterjet cut samples (8 %).[2] Therefore, the mechanical cut method is not presented in this practice.

1.6 Only the laminate area of the PV module is considered for TCLP testing, as other possible module parts, such as aluminum frame, junction box and cables contain recyclable materials that are already well-documented and are not specific to the PV modules.

1.7 The material gravimetric density (g/cm^3) throughout the laminate area is considered constant.

1.8 This practice was developed to be consistent with three fundamental requirements:

1.8.1 Sample pieces with particle size not to exceed the allowed size limit of EPA 1311 standard which is 9.5 mm,

1.8.2 The particle size used in this practice as sample piece is consistent with the median particle size expected in landfill disposal[2], and

1.8.3 An assumption that each laminate sample piece will result in 100 % glass coverage area, due to the presence of bonding encapsulant layers once it is broken in the landfill.

1.9 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.10 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.11 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standard:*[3]

D4538 Terminology Relating to Protective Coating and Lining Work for Power Generation Facilities

E772 Terminology of Solar Energy Conversion

[1] This practice is under the jurisdiction of ASTM Committee E44 on Solar, Geothermal and Other Alternative Energy Sources and is the direct responsibility of Subcommittee E44.09 on Photovoltaic Electric Power Conversion.

Current edition approved Nov. 1, 2021. Published December 2021. DOI: 10.1520/E3325-21.

[2] TamizhMani, G., Libby, C., Shaw, S., Krishnamurthy, R., Leslie, J., Yadav, R., Tatapudi S., and Bicer, B. "Evaluating PV Module Sample Removal Methods for TCLP Testing," IEEE Photovoltaic Specialists Conference, June 2018.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

2.2 *EPA Methods:*[4]

Test Method 1311 Toxicity Characteristic Leaching Procedure

Method 6010C (SW-846) Inductively Coupled Plasma - Atomic Emission Spectrometry

Method 7470A (SW-846) Mercury in Liquid Wastes (Manual Cold-Vapor Technique)

3. Terminology

3.1 Definitions of Terms used in this practice may be located in Terminology E772

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *cell area, n*—the area of all the cells in the laminate excluding the cell ribbon/interconnect area, string-ribbon area and non-cell/non-ribbon area.

3.2.2 *cell-ribbon area, n*—the area of all the cell interconnect ribbons in the laminate excluding cell area, string-ribbon area and non-cell/non-ribbon area.

3.2.3 *laminate, n—of a PV module*, a stack of layers that are laminated together with superstrate (typically, glass), encapsulant (typically, polymeric material), solar cell and substrate (typically, polymeric sheet). A laminate does not include the frame and junction box of the module.

3.2.4 *non-cell/non-ribbon area (electrically inactive area), n*—the sum of all the areas (including the area embedded inside the groove of the frame) which are not covered by the cells, cell ribbons/interconnects and string ribbons.

3.2.5 *string-ribbon area, n*—the area of all the string ribbons in the laminate excluding cell area, cell-ribbon area and non-cell/non-ribbon area.

3.2.6 *total laminated area, n*—a sum of three or four areas – cell area, cell-ribbon area (c-Si modules only), string-ribbon area and non-cell/non-ribbon area.

4. Apparatus

4.1 *Waterjet Cutting Facility*—Waterjet cutting is an erosive process that uses high-pressure water to cut through the laminate for obtaining sample pieces required for the TCLP testing, typically provided by third-party waterjet cutting companies. An important benefit of the waterjet is the smooth cut with 100 % glass coverage in the cut pieces and ability to cut material without separating layers of the laminate into glass, encapsulant, cell and backsheet/backglass, as there is no heat-affected zone and glass vibration is minimized. Square pieces with each side not more than 9.5 mm in length are cut with the waterjet. These square pieces can be cut individually, or in the following two-step process. Initially, linear strips are cut with a width of 9.5 mm from each of the different laminate areas. In a second step, these strips will be placed on the waterjet machine and individual sample pieces will be cut as square pieces with each side not more than 9.5 mm in length.

4.2 *Convection Oven*—An oven used to dry the sample pieces at 50 °C by evenly distributing the heat around the sample pieces.

4.3 *Deionized Water*—Deionized water is the water that contains no mineral ions. "Deionized water, —water that has been purified of salts by passing through a cation-exchange resin to replace metal ions, such as calcium and iron, with the hydrogen ion and through an anion-exchange resin to remove both the hydrogen ions and the corresponding negative ions." [D4538]

5. Summary of Practice

5.1 This practice presents a representative and repeatable methodology to remove sample pieces from PV modules for later use in the TCLP testing. This practice refers to the extraction and preparation of PV module sample pieces complying to the EPA Method 1311 for later testing to eight (8) distinct metals – mercury (by Method 7470A), arsenic, barium, cadmium, chromium, lead, selenium and silver (by Method 6010C) as well as the analysis and interpretation of the TCLP test results on a module level.

5.2 Sample pieces must be 9.3 by 9.3 – 9.5 by 9.5 mm square.

5.3 The total weight of all sample pieces must be a minimum of 100 g for TCLP testing, plus 5–10 g for pH testing.

5.4 For both module types (crystalline silicon and cadmium telluride), the following step-wise procedure is used:

5.4.1 Measure the required areas of the module; these differ for crystalline-Si (four areas) and CdTe (three areas) modules.

5.4.2 Calculate the percentage of the total laminate area for each required area.

5.4.3 Estimate the number of samples needed from the total weight of samples needed divided by the average weight of a sample piece.

5.4.4 Remove samples using the waterjet cutting approach.

5.4.5 Rinse and dry samples.

5.4.6 Group samples according to the areas from which they were removed.

5.4.7 Weigh all samples in each area group.

5.4.8 Calculate the number of samples needed for each area group.

5.4.9 Verify that the samples meet the total weight in 5.3.

5.4.10 Submit the samples for TCLP testing.

6. Significance and Use

6.1 The primary goal of this practice is to extract representative samples from PV modules for TCLP toxicity testing purposes in order to receive unbiased, comparable and repeatable toxicity test results from independent TCLP testing laboratories.

6.2 Solar photovoltaic (PV) modules in the United States and the world reaching end-of-life due to failure, underperformance or breakage due to extreme weather have to be recycled or otherwise safely disposed of following the Resource Conservation and Recovery Act (RCRA) regulation [United States, Resource Conservation and Recovery Act. Pub.L. 94–580,

[4] Available from United States Environmental Protection Agency (EPA), William Jefferson Clinton Bldg., 1200 Pennsylvania Ave., NW, Washington, DC 20460, http://www.epa.gov.

October 1976]. For end-of-life PV modules, the U.S. Environmental Protection Agency (EPA) Method 1311 (TCLP) is used for waste characterization based on leaching potential under simulated landfill conditions.

6.3 Commercial PV modules contain compounds and alloys of various metals (for example, Ag, Al, Cd, Cu, Ga, In, Ni, Pb, Se, Sn, Te, Zn) which are used in semiconductor compounds and electrical contacts.[5] Modules that pass the EPA Method 1311 TCLP test, and state protocols (if applicable), can be disposed of in a regular landfill. Otherwise, they are classified as hazardous waste and must go through a more onerous and expensive disposal process. Currently, there is no national or international standard, nor a standardized protocol available for removal of test samples from PV modules for toxicity testing per the EPA Method 1311 standard.

6.4 The validity of the toxicity test results heavily depends on the location of extracted samples in the module, specifically within the laminate area, and the particle size of the extracted samples. Therefore, it is critical that the sample extraction procedure be properly designed to avoid biased or otherwise inaccurate toxicity test results.

6.5 The development and application of a homogeneous and representative sampling standard will help utilities and manufacturers to limit the number of variables and to obtain repeatable test results.

7. Procedure

7.1 *Sampling Procedure for Crystalline Silicon PV Modules:*

7.1.1 A typical crystalline silicon PV module incorporates 60 or 72 cells and consists of the *(1)* frame; *(2)* laminate; *(3)* junction box; and *(4)* cables and connectors. The total laminate area of the module can be divided into four representative parts, as indicated in Fig. 1 for a crystalline silicon PV module.

7.1.2 *Pre-Removal Calculation Procedure:*

7.1.2.1 The pre-removal preparation procedure is divided into three major steps: *(1)* calculation of total laminate area; *(2)* calculation of individual laminate areas as shown in Fig. 1; and *(3)* initial calculation of number of pieces to remove per laminate area.

7.1.2.2 To accurately calculate the total area of the laminate for a framed c-Si module (Fig. 2), it is important to remember that a small area of the laminate area is hidden under the frame. The length from the hidden edge of the laminate to the outer edge is called the groove thickness (l_3) and is typically around 5 mm.

Calculate the total area of the laminate (A_l) using the following equation:

$$A_l = [l_1 - (2 \times l_3)] \times [l_2 - (2 \times l_3)] \text{mm}^2$$

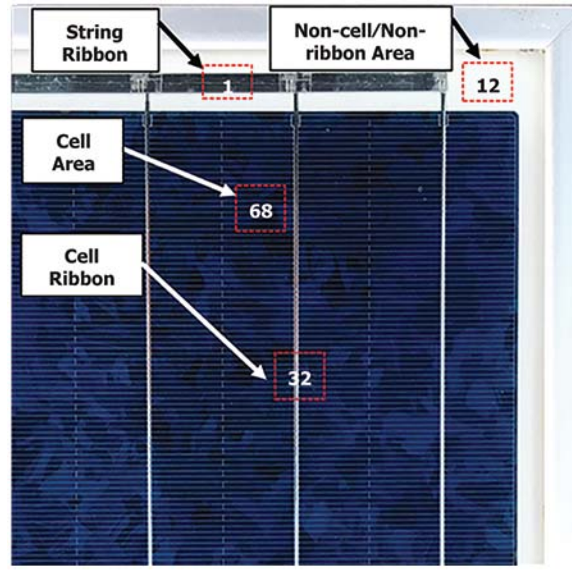

FIG. 1 Laminate Area of a Multi-crystalline PV Module With Representative Sampling Locations (the numbers inside the squares indicate the approximate number of required 9.5 mm by 9.5 mm pieces in a typical c-Si module)

Example 1:

Length of the module including frame (l_1)	= 1956 mm
Width of the module including frame (l_2)	= 992 mm
Groove thickness (l_3)	= 5 mm (default value)
Total laminate area (A_l)	= [1956 – (2 × 5)] × [992 – (2 × 5)]
	= **1 910 972 mm²**

7.1.2.3 Conduct the following measurements to calculate the proportional areas of cell, cell ribbon, string-ribbon and non-cell/non-ribbon for a crystalline PV module (Fig. 3):

(1) Count the number of cells in module laminate (N_{cl}).

(2) Measure the length (l_1) and width (l_2) of one cell, including the lengths to which the cut corners would have met.

(3) Measure the length (c_1) and width (c_2) of one cut corner (if monocrystalline silicon module, otherwise c_1 and c_2 are 0 mm).

(4) Calculate the area of one cell:

$$A_{cell} = [(l_1 \times l_2) - ((c_1 \times c_2)/4)] \text{mm}^2$$

(5) Count the number of cell ribbons in one cell (N_{cr}) and measure the length (l_3) and width (l_4) of one cell ribbon within one cell.

(6) Calculate the area of cell ribbons (A_{cr}) in one cell:

$$A_{cr} = [(l_3 \times l_4) \times N_{cr}] \text{ mm}^2$$

(7) Calculate the total cell-ribbon area (A_{crl}) in the total module laminate:[6]

$$A_{crl} = (A_{cr} \times N_{cl}) \text{ mm}^2$$

(8) Calculate the net cell area for one cell (A_c) without cell ribbons:

$$A_c = (A - A_{cr}) \text{ mm}^2$$

(9) Calculate the total cell area (A_{crl}) in module laminate:

[5] Human Health Risk Assessment Methods for PV Part 3: Module Disposal Risks, https://iea-pvps.org/key-topics/human-health-risk-assessment-methods-for-pv-part-3-module-disposal-risks/

[6] As intercell ribbon length is negligibly small compared to the ribbons on the surfaces of the cells, they were not included in the calculation.

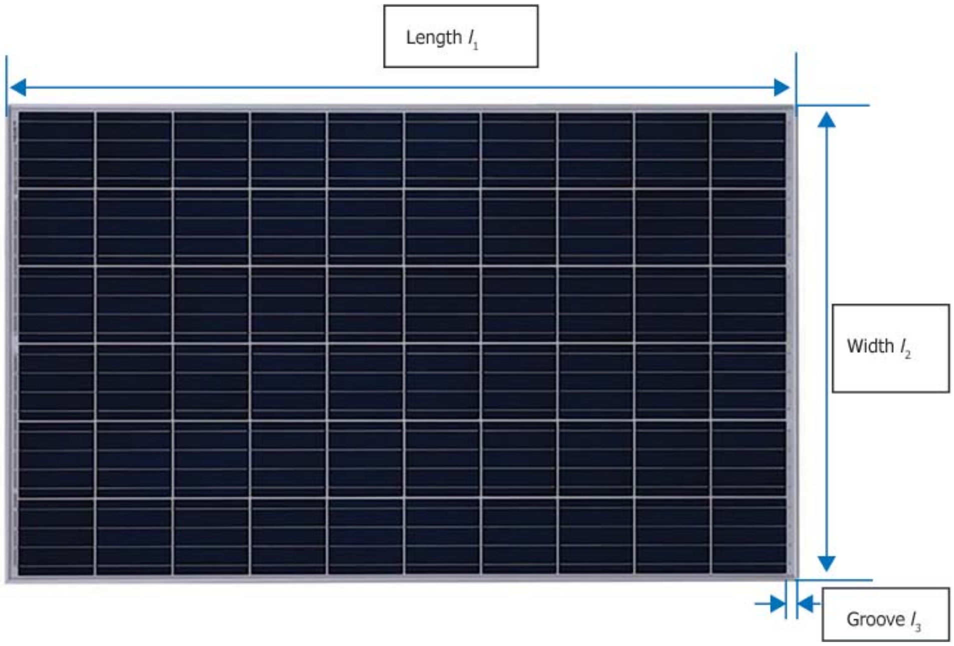

FIG. 2 Frontside of a c-Si PV Module

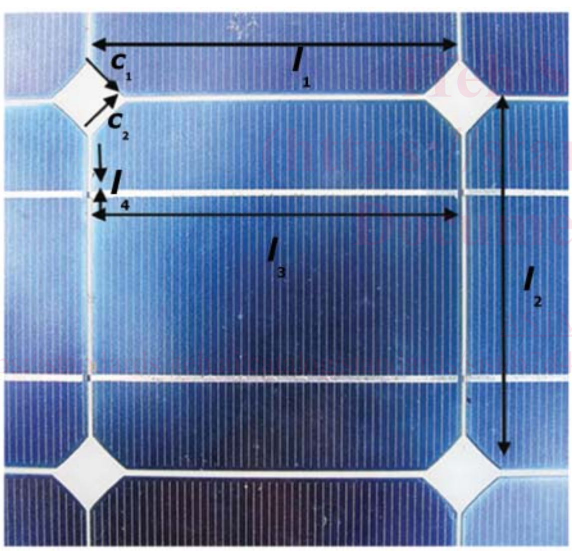

FIG. 3 Close-up of One Cell in a Mono-crystalline PV Module

$$A_{cl} = (A_c \times N_{cl})\ \text{mm}^2$$

(10) Count the number of string ribbons (N_{srl}) in module laminate and measure the length (l_5) and width (l_6) of each string ribbon.

(11) Calculate the area of all string ribbons (A_{srl}) in module laminate:[7]

$$A_{srl} = [(l_5 \times l_6) \times N_{srl}]\ \text{mm}^2$$

(12) Calculate the non-cell/non-ribbon area (A_{ncnr}) in module laminate:

$$A_{ncnr} = [A_1 - (A_{cl} + A_{crl} + A_{srl})]\ \text{mm}^2$$

[7] There might be several string ribbons with different dimensions in one module. If so, include all string ribbons in the calculation by summing all individual ribbon areas.

Example 2:

Monocrystalline Si PV module with 72 cells

Length of 1 cell (l_1)	= 155 mm
Width of 1 cell (l_2)	= 155 mm
Length of cell corner (c_1)	= 10 mm
Width of cell corner (c_2)	= 10 mm
Number of cell ribbons in 1 cell	= 5
Length of cell ribbon	= 155 mm
Width of cell ribbon	= 1 mm
Number of string ribbon 1(#sr1)	= 3
Length of string ribbon 1	= 290 mm
Width of string ribbon 1	= 6 mm
Number of string ribbon 2(#sr2)	= 1
Length of string ribbon 2	= 930 mm
Width of string ribbon 2	= 6 mm

Total cell area in laminate (A_{cl}) = [(155 × 155) – ((10 × 10)/2 × 4) – ((155 × 1) × 5) × 72] = 1 659 600 mm^2
Total cell-ribbon area in laminate (A_{crl})= [(155 × 1) x 5] × 72 = 55 800 mm^2
Total string-ribbon area in laminate (A_{srl}) = [(290 × 6) × 3] + [(930 × 6) x 1] = 10 800 mm^2
Total non-cell/non-ribbon area (A_{ncnr}) = 1 910 972 – (1 659 600 + 55 800 + 10 800) = 184 772 mm^2

7.1.2.4 Calculate the proportional values for each area in relation to the whole laminate area based on the individual calculations of each dedicated laminate area in Step 2:

(1) Cell area in % = A_{cl}/A_l × 100 %
(2) Cell-ribbon area in % = A_{crl}/A_l × 100 %
(3) String-ribbon area in % = A_{srl}/A_l × 100 %
(4) Non-cell/Non-ribbon area in % = A_{ncrn}/A_l × 100 %

Example 3A:

Cell area in %	= 1 659 600 / 1 910 972 ×100 % = 86.8 %
Cell ribbon area in %	= 55 800 / 1 910 972 × 100 % = 2.9 %
String ribbon area in %	= 10 800 / 1 190 972 × 100 % = 0.6 %
Non-cell/Non-ribbon area in %	= 184 772 / 1 190 972 × 100 % = 9.7 %

7.1.2.5 Calculate the estimated number of samples that need to be removed from each dedicated laminate area. The minimum sample weight to be supplied for TCLP testing, as mandated by EPI SW-846 Test Method 1311, is 100 g. In addition, 5-10 g of sample pieces are supplied separately to the laboratories for pH tests only. In order to avoid further particle reduction at the test laboratory, it is also assumed that each individual sample piece will be less than 9.5 mm (typically, 9.2 mm - 9.5 mm) on each side or in diameter. The average weight of a square laminate sample with 9.5 mm by 9.5 mm dimensions has been measured as 0.87 g[8]. Each cell-ribbon area piece contains both cell ribbon and cell areas. Thus, every extracted square cell-ribbon area piece (9.5 mm by 9.5 mm), only contains 10.5 % (1 mm ribbon in width; see Example 2) of actual cell-ribbon and 89.5 % is pure cell area. This needs to be accounted for in the calculation. Estimate the number of total samples pieces and the number of sample pieces per laminate area as follows:

(1) Estimated total number of samples (N_t) required (for 100 g):

$$N_t = 100\text{ g}/0.87\text{ g} = 115$$

(2) Estimated number of samples from cell-ribbon area (N_{cr}):

$$N_{cr} = (N_t \times \text{cell} - \text{ ribbon area in } \% / 100 \%) \times 0.1$$

(3) Number of samples from cell area:

$$N_c = (N_t \times \text{cell area in } \% / 100 \%) - (N_{cr} \times 0.9)$$

(4) Number of samples from string-ribbon area (N_{sr}):

$$N_{sr} = N_t \times \text{string} - \text{ ribbon area in } \% / 100 \%$$

(5) Number of samples from non-cell/non-ribbon area (N_{ncnr}):

$$N_{ncnr} = N_t \times \text{non} - \text{cell/ non} - \text{ribbon area in } \% /100 \%$$

Example 3B (all results are rounded up):

Average weight of 1 square sample	= 0.87 g
Total weight of waste to be submitted to TCLP lab	= 100 g
Estimated number of samples required	= 100 / 0.87 = 115
Estimated number of samples from cell-ribbon area	= 115 × 0.03 / 0.1 = 35
Estimated number of samples from cell area	= (115 × 0.87) – 35 = 66
Estimated number of samples from string-ribbon area	= 115 × 0.01 = 1
Estimated number of samples from non-cell/non-ribbon area	= 1150 × 0.107 = 12

7.1.3 Send the module to a waterjet cutting facility. The waterjet cutting approach slices the PV modules using a jet of water (or a mixture of water and an abrasive substance) at high velocity and pressure.

7.1.4 *Post-Removal Calculation Procedure:*

7.1.4.1 Rinse all samples which were extracted with the waterjet removal method in deionized water and dry them in a convection oven at ≤50 °C for at least 4 h. Subsequently, group all samples into the four laminate areas, *(1)* cell area; *(2)* cell-ribbon area; *(3)* string-ribbon area; and *(4)* non-cell/non-ribbon area.

7.1.4.2 Weigh each laminate group collectively (W_t) and count the number of samples for each group (N_t). Subsequently, calculate the average weight for one sample by laminate group as follows:

(1) Average weight for one sample from cell area = W_{tc} / N_{tc}

(2) Average weight for one sample from cell-ribbon area = W_{tcr} / N_{tcr}

(3) Average weight for one sample from string-ribbon area = W_{tsr} / N_{tsr}

(4) Average weight for one sample from non-cell/non-ribbon area = W_{tncrn} / N_{tncrnr}

Example 4:

Number of cell area samples	= 100
Total weight of all cell area samples	= 80 g
Average weight of cell area sample	= 0.8 g
Number of cell-ribbon area samples	= 100
Total weight of all cell-ribbon area samples	= 80 g
Average weight of cell-ribbon area sample	= 0.8 g
Number of string-ribbon area samples	= 20
Total weight of all string-ribbon area samples	= 12 g
Average weight of string-ribbon area sample	= 0.6 g
Number of non-cell/non-ribbon area samples	= 20
Total weight of non-cell/non-ribbon area samples	= 12 g
Average weight of non-cell/non-ribbon area sample	= 0.6 g

7.1.4.3 Calculate the number of samples by laminate area based on the total sample weight of at least 100 g to be supplied for TCLP testing and the respective proportional values for each of the four laminate areas. It is important to point out that each cell-ribbon area sample contains both cell ribbon and cell areas. Thus, every extracted square cell-ribbon area sample (9.5 mm by 9.5 mm), only contains 10.5 % (1 mm ribbon in width; see Example 2) of actual cell-ribbon and 89.5 % is pure cell area:

(1) Number of samples from cell-ribbon Area:

$$N_{cr} = (100\text{ g} \times A_{crl} / A_l) / (W_{tcru} \times 0.1)$$

(2) Number of samples from cell area:

$$N_c = (100\text{ g} \times A_{cl} / A_l)/W_{tcu} - (N_{cr} \times 0.9)$$

(3) Number of samples from string-ribbon area:

$$N_{sr} = (100\text{ g} \times A_{srl}/A_l) / W_{tsru}$$

(4) Number of samples from non-cell/non-ribbon area:

$$N_{ncnr} = (100\text{ g} \times A_{ncrn} / A_l) / W_{tncnru}$$

(5) Total number of samples:

$$N_t = N_c + N_{cr} + N_{sr} + N_{ncnr}$$

Example 5:

Number of samples from cell-ribbon area	= (100 g × 0.029)/(0.8 g × 0.1) = 35
Number of samples from cell area	= (100 g × 0.868)/0.8 g – (39 × 0.9) = 78
Number of samples from string-ribbon area	= (100 g × 0.006)/0.6 g = 1
Number of samples from non-cell/non-ribbon area	= (100 g × 0.097)/0.6 g = 17
Total number of samples	= 35 + 78 + 1 + 17 = 131

7.1.4.4 Weigh all sample pieces together, as calculated by the laminate area in Step 5, in order to verify the total sample weight of approximately 100 g. Place the sample pieces subsequently in a small container and send them to the TCLP testing laboratory with a clear instruction on the sample

[8] This is an estimate used to calculate how many pieces to remove from the module and comprise a single sample. Final weights re-determined after the extraction of samples.

container to not reduce the number of supplied pieces or sizes of the pieces for the TCLP testing. Place approximately 10 g of the sample in another small container for pH testing of the sample by the TCLP laboratory.

Example 6:

Total weight of samples = 35 × 0.8 g + 78 × 0.8 g +1 × 0.6 g +17 × 0.6 g = 101.2 g

7.2 *Sampling Procedure for Cadmium Telluride PV Modules:*

7.2.1 A typical cadmium telluride (CdTe) thin-film PV module incorporates up to 264 cells in one module and consists of the laminate, one or more junction boxes, and module leads and connectors. The total laminate area of the module can be divided into three representative parts, as indicated in Fig. 4 for a cadmium telluride PV module.

7.2.2 In CdTe modules, the cell area is practically covering the whole front side of the module, as indicated in Fig. 1. The cell area is just slightly smaller than the module area as it is enclosed by the non-cell/non-ribbon area around the perimeter of the module. The string ribbons are easily visible and measurable from the backside of the CdTe module. In the example of Fig. 1, there are three string ribbons along the width of the module, one on each edge and one in the middle of the module, as well as one ribbon across the whole length of the module.

7.2.3 *Pre-removal Calculation Procedure:*

7.2.3.1 The preparation procedure is divided into three major steps: *(1)* calculation of total laminate area; *(2)* calculation of individual laminate areas; and *(3)* estimated calculation of number of pieces to remove per laminate area.

7.2.3.2 Calculate the total area of the laminate (A_l) for frameless CdTe modules or for CdTe modules with under-mount frame (Fig. 5):

$$A_l = (l_1 \times l_2)\ \text{mm}^2$$

Example 7: CdTe PV Module

Length of the module (l_1)	= 1200 mm
Width of the module (l_2)	= 600 mm
Total laminate Area (A_l)	= (1200 × 600) = 720 000 mm² (0.72 m²)

7.2.3.3 Conduct the following measurements to calculate the proportional areas of cell, string ribbon and non-cell/non-ribbon (Fig. 6):

(1) Measure the width (l_3) of the non-cell/non-ribbon area.[9]

(2) Count the number of string ribbons (N_{sr4}) going across the width of the module and the number of string ribbons (N_{sr5}) going across the length of the module.

(3) Measure the width (l_4) of the string ribbons going across the width of the module.[10]

(4) Measure the width (l_5) of the string ribbon going across the length of the module.

(5) Calculate the total cell area (A_{cell}) in module laminate:

$$A_{cell} = [(l_1 - 2 \times l_3) \times (l_2 - 2 \times l_3)]\text{mm}^2$$

(6) Calculate the total non-cell/non-ribbon area (A_{ncnr}) in module laminate:

$$A_{ncnr} = [A_l - A_{cell}]\text{mm}^2$$

(7) Calculate the total area of all string ribbons (A_{srl}) in module laminate[11]:

$$A_{srl} = N_{sr4} \times (l_4 \times (l_2 - 2 \times l_3)) + N_{sr5} \times (l_5 \times (l_1 - 2 \times l_3))\ \text{mm}^2$$

Example 8: CdTe PV Module

Length of the module (l_1)	= 1200 mm
Width of the module (l_2)	= 600 mm
Total laminate area (A_l)	= (1200 × 600) = 720 000 mm² (0.72 m²)

[9] It is assumed that the width of the non-cell/non-ribbon area is constant along all four sides.

[10] It is assumed that the widths of the vertical string ribbons are identical.

[11] There might be several string ribbons with different dimensions in one module. If so, include all string ribbons in the calculation by summing all individual ribbon areas.

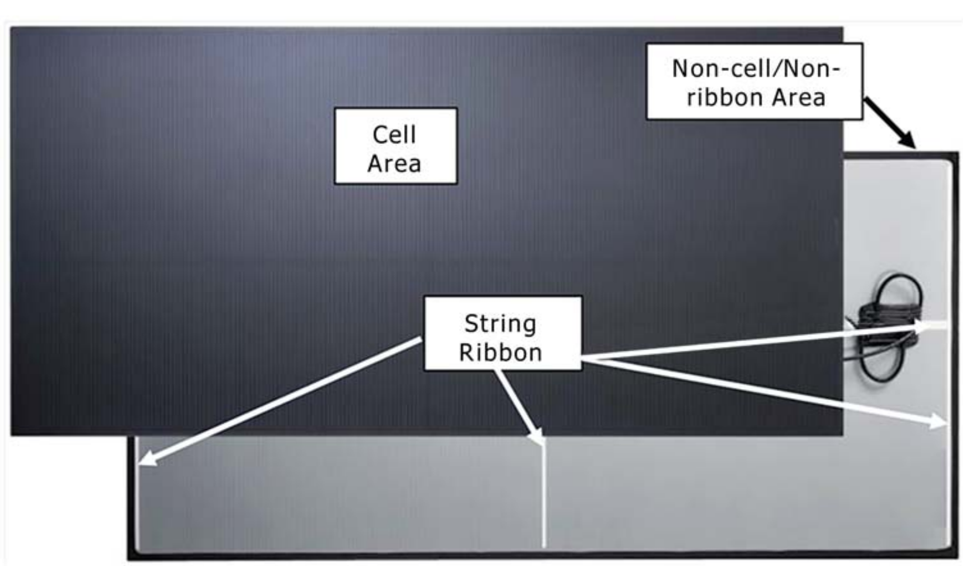

FIG. 4 Front and Backside of a CdTe PV Module

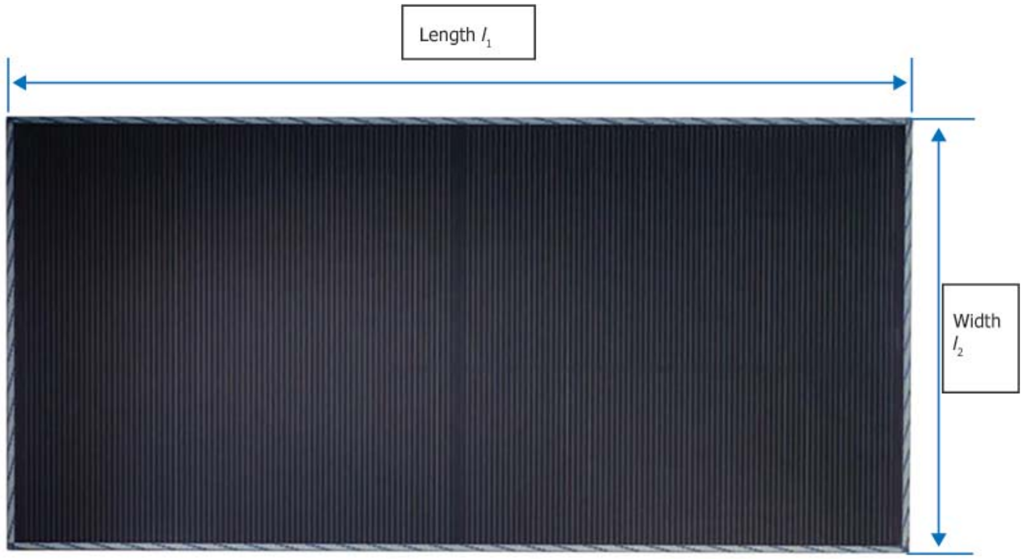

FIG. 5 Frontside of a CdTe PV Module

FIG. 6 Front and Back-side of a CdTe PV Module

Example 9: CdTe PV Module (based on Fig. 6)

Width of non-cell/non-ribbon area (l_3)	= 7 mm
Number of string ribbons across width (Nsr_4)	= 3
Number of string ribbons across length (Nsr_5)	= 1
Width of string ribbon across width (l_4)	= 5 mm
Width of string ribbon across length (l_5)	= 15 mm
Total cell area in laminate (A_{cell})	
= [(1200 – 2 × 7) (600 – 2 × 7)]	= 694 996 mm^2
Total non-cell/non-ribbon area in laminate (A_{ncnr})	
= [720 000 – 694 996]	= 25 004 mm^2
Total string-ribbon area in laminate (A_{srl})	
= [3 × (5 × (600 – 2 × 7)) + 1 × (15 × (1200 – 2 × 7))]	= 26 580 mm^2

7.2.3.4 Calculate the proportional values for each area in relation to the whole laminate area as follows:[12]

(1) Cell area in % = $A_{cell}/A_l \times 100$ %
(2) String-ribbon area in % = $A_{srl}/A_l \times 100$ %
(3) Non-cell/Non-ribbon area in % = $A_{ncrn}/A_l \times 100$ %

Example 10A: CdTe PV Module:

Cell area in %	= 694 996 / 720 000 × 100 % = 96.5 %
String ribbon area in %	= 26 580 / 720 000 × 100 % = 3.7 %
Non-cell/Non-ribbon area in %	= 25 004 / 720 000 × 100 % = 3.5 %

7.2.3.5 Calculate the estimated number of samples that need to be removed from each dedicated laminate area. The minimum sample weight to be supplied for TCLP testing, as mandated by EPI SW-846 Test Method 1311, is 100 g. In addition, 5-10 g of sample pieces are supplied separately to the laboratories for pH tests only. In order to avoid further particle reduction at the test laboratory, it is also assumed that each individual sample piece will be not more than 9.5 mm on each side or in diameter. The average weight of a square laminate

[12] As string ribbons are below the cell area, the sum of the individual areas will exceed 100 %. This will be accounted for in the calculation of the individual sample pieces per laminate area.