Photovoltaic Module Grounding: Addendum Report on Corrosion Testing

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EXECUTIVE SUMMARY

This report is an addendum to a two-part study addressing the electrical grounding of photovoltaic (PV) modules. The Solar America Board for Codes and Standards (Solar ABCs), with support from the U.S. Department of Energy, commissioned the study to provide the PV industry with practical guidelines for module grounding and recommendations for improving product standards that certify modules and related grounding components. Solar ABCs published an interim "Lay of the Land" report on the topic in the spring of 2011, which described the many issues facing industry stakeholders. A final report documenting guidelines, safety considerations, and recommended changes to existing codes and standards, was published in April 2012. This addendum provides updated information and recommendations related to corrosion testing of module grounding components and connections.

The 2012 report addresses issues related to corrosion testing of PV module ground connections, but noted the need for subsequent updates given the level of activity occurring at the time of publication. That report presented details of a 2011 Underwriters Laboratories (UL) paper (Wang, Yen, Wang, Ji, & Zgonena, 2011) summarizing exploratory testing of different types of PV module grounding (bonding) devices in environmental chambers using both continuous damp heat and salt mist environmental exposure. The effects of current cycling, assembly force, and antioxidation coating application on grounding reliability were evaluated in conjunction with aging tests.

The study was noteworthy for the dramatic failure of components occurring during salt-mist exposure tests. Although it provided a great deal of valuable information, the study also raised questions about the appropriateness of the extreme conditions defined by the existing corrosion test standards in determining the performance of components in actual PV array field conditions.

In this addendum, we recommend adoption of newly published salt-mist test procedures in International Electrotechnical Commission (IEC) Standard 61701 (IEC, 2011): "Salt mist corrosion testing of photovoltaic (PV) modules." This standard specifically addresses testing issues particular to PV module frames and adopts cycling methods that better approximate the conditions experienced by PV components in a marine environment. We also recommend the adoption of procedures published in IEC 62716 (IEC, 2012), "Ammonia corrosion testing of photovoltaic (PV) modules." These tests are intended to address modules operating in highly corrosive wet atmospheres near agricultural or other industrial facilities.

Finally, we identify information and lessons learned from ongoing UL 2703 (UL, 2011) certification testing of module grounding components. This provides insight into the materials that are proving effective in corrosion testing as well as those that are not. This information has helped to identify less ambiguous criteria for determining the compatibility of various dissimilar metals.

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Solar America Board for Codes and Standards

The Solar America Board for Codes and Standards (Solar ABCs) provides an effective venue for all solar stakeholders. A collaboration of experts formally gathers and prioritizes input from groups such as policy makers, manufacturers, installers, and large- and small-scale consumers to make balanced recommendations to codes and standards organizations for existing and new solar technologies. The U.S. Department of Energy funds Solar ABCs as part of its commitment to facilitate widespread adoption of safe, reliable, and cost-effective solar technologies.

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Introduction

This report is an addendum to a two-part study of photovoltaic (PV) module grounding issues. Solar ABCs published interim and final reports from the study in 2011 and 2012, which discussed a wide range of module grounding issues; provided guidelines for designers, installers, and inspectors; and made recommendations for the evolving standards. This addendum focuses on corrosion issues and test recommendations based on developments that were ongoing at the time the previous reports were written. The subject is by no means closed and the industry has work to do to resolve issues of component reliability and certification. However, newly published International Electrotechnical Commission (IEC) standards provide a good model for improving certification tests, and generalized findings from recent Underwriters Laboratories (UL) certification tests offer valuable direction and guidelines for product manufacturers and designers.

PV modules are typically installed on aluminum or galvanized, painted, or stainless steel frame structures. These structures and any other electrically conductive components that could become energized by the PV array (or other electricity sources) and that could be accessible during routine servicing must be grounded to ensure safe touch voltages. The study addressed problems the industry faced with respect to limited grounding methods and equipment certification paths for components, and sought to address the issues with the following steps:

1. Publication of an interim Lay of the Land report, a survey of the existing situation in which stakeholders (system designers, module and component manufacturers, Nationally Recognized Testing Laboratories [NRTLs], and researchers) shared their experiences and recommendations to address the issues listed above. This interim report was published in the spring of 2011.
2. Evaluation of existing and new test procedures. This was primarily a UL-led effort to investigate expanded or enhanced current and accelerated aging test methods that can provide greater confidence in the long-term reliability of grounding methods.
3. Development of a final report making final recommendations for new or expanded tests to incorporate into standards, and documenting guidelines and procedures for public use. This report was published in April 2012.

Throughout this study's documents, the terms "ground," "grounding," and "grounded" are used to describe the connections to module frames that are the primary focus of the study. Note that there is a distinction between "grounded" and "bonded." Article 100 of the 2011 *National Electrical Code* (NFPA, 2011) defines these terms as follows:

- Grounded: Connected to ground or to a conducting body that extends the ground connection.
- Bonded: Connected to establish electrical continuity and conductivity.

The scope of the study focuses on the bonding of frames to other parts or conductors that are then grounded. This report uses the more general "grounding" term to describe both bonding and grounding unless bonding is specifically called out.

The applicable standards for evaluation and certification of module frame grounding are:

UL 1703: Flat-Plate Photovoltaic Modules and Panels
UL 1703 (UL, 2008) is the "primary" standard affecting module grounding and devices. Methods certified to UL 1703 and documented in module manufacturers' installation instructions are almost universally accepted by inspectors and authorities having jurisdiction. UL 1703 covers a range of safety and construction related requirements for modules, with a few sections dedicated to frame bonding, grounding, and continuity. It also establishes requirements for the means of grounding as well as continuity requirements subject to applied current and environmental (accelerated life) testing.

UL 2703: Rack Mounting Systems and Clamping Devices for Flat-Plate Photovoltaic Modules and Panels
UL 2703 (UL, 2011) is a new draft standard, meaning it is not yet an American National Standards Institute (ANSI) standard. It was created to address PV module mounting systems. It covers mechanical and other general issues for mounting systems, including grounding. The grounding section incorporates much of the same language used in UL 1703, applied broadly to the mounting system components. UL 2703 enables manufacturers to list individual grounding components independent of the racking certification. There is also a mechanism for establishing subsystem level testing of bonding—tests using multiple modules and components connected together, rather than single connections, for example—and impedance requirements for metal apparatus containing multiple strings of modules. The development of UL 2703 is a significant benefit to the PV industry as it provides a direct means for evaluating the use of structural hardware for grounding purposes.

MODULE GROUNDING AND CORROSION

One of the common failure modes of module grounding identified in the Lay of the Land report is corrosion of the bonds and connections. Failures from corrosion can have many causes. Galvanic corrosion resulting from the joining of dissimilar metals is probably the most common general cause. However, corrosion can also occur as a result of long-term exposure of components to cycling leakage current, which produces an electrolysis process. Failures due to corrosion can be attributed to the following general causes:

- Improper selection of materials for the bonded connection. Copper and aluminum bonds are the most common and have dramatic results, but other less obvious combinations may break down over time.
- Dissimilar metals in close proximity, which—depending on the electrolyte involved—causes corrosion when exposed to water, soil, or other conductive debris elements.
- Insufficient barriers between dissimilar metals, such as undersized or improperly installed stainless steel washers separating copper and aluminum.
- Good but inadequately protected connections after long-term exposure to leakage current, water, salt-humidity, and/or other corrosive agents. An example is a tin-coated assembly joining a copper wire and aluminum frame where the coating is inadequate to serve as a sacrificial barrier over the long term.

The following photos illustrate the destructive nature of the corrosive degradation in module grounding connections. The final photograph shows a newly installed bonding connection that appears fine at the outset but is destined to degrade due to the direct joining of copper and aluminum.

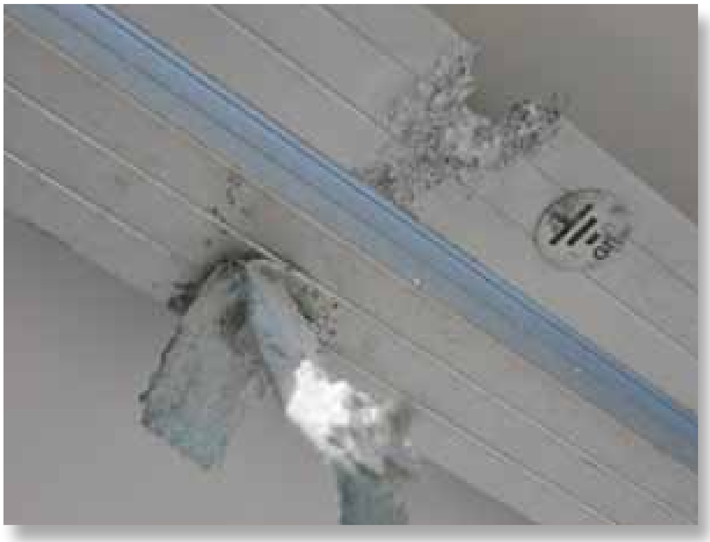

Figure 1: Corrosion between copper ground braid, stainless steel screw, and aluminum frame.

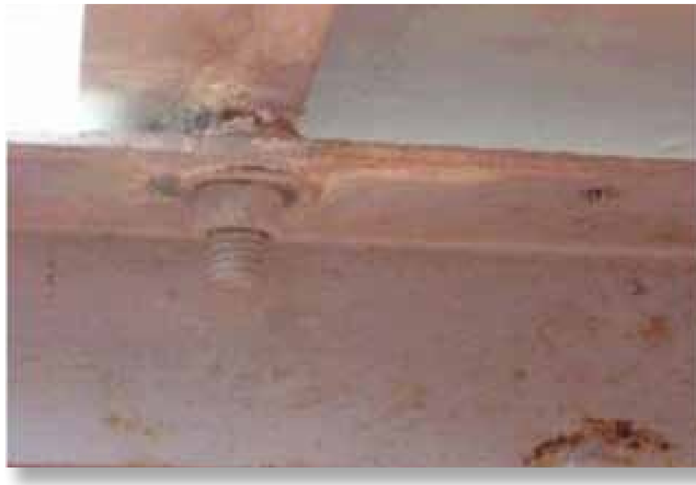

Figure 2: Corrosive degradation in a harsh environment.

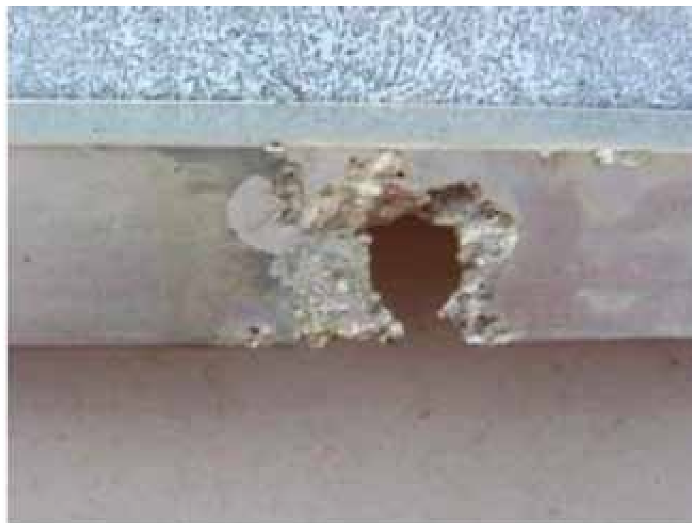

Figure 3: Lost connection from corrosive bond.

Figure 4: Connection of dissimilar (incompatible) materials, before corrosion begins. Photo credit (Figures 1-4): John Wiles, Southwest Technology Development Institute, New Mexico State University

CORROSION DEFINED

Corrosion is the chemical reaction process that takes place in metals (or other materials), usually as a result of electrochemical oxidation, resulting in the gradual destruction of the metals. Galvanic corrosion, the type of corrosion that occurs in electrical connections, is a specific electrochemical process that occurs when two metals of different electrochemical potentials are in contact in some form of electrolyte. This combination allows current to flow from one metal (the anode), to the other (the cathode), potentially causing a destructive degradation of the anode material. The electrolyte for electrical connections of this type may be a liquid solution as in the case of batteries, but in the context of PV modules it is the environment of the installation, such as damp, humid air, possibly with salt content (such as near an ocean), dirt, or rain containing acids and alkalis.

The rate and aggressiveness of corrosion depends on many factors, but the primary issues are the electrical conductivity of the electrolyte, the difference of electrode potential between the metals, and the characteristics of the connection, such as the ratio between the cathode area and anode area. Corrosion is also more severe with direct currents than with alternating currents. Corrosion of the anode can actually reduce or prevent the corrosion process of the cathode. This is the basis for the use of sacrificial anode layers, which are material coatings or layers that allow a small area of metal to intentionally corrode and effectively halt additional corrosion of the more important materials while still maintaining the conductive function of the connection.

In electrical bonding connections such as module bonding or grounding, the primary cause of corrosion is the connection of dissimilar metals with incompatible electrochemical potential, and/or the aggressiveness of the environmental electrolyte, as discussed in the previous section.

CORROSION AND CURRENT STANDARDS

Both of the previous reports in this study discussed the numerous paths that have led to unnecessarily corroded grounding bonds. At a high level, the three contributing factors have been:

1. installation errors, which encompass incorrect use or installation of parts, improperly written instructions from manufacturers, or carelessness;
2. parts and components that have not been adequately tested to demonstrate resistance to corrosion; and
3. lack of adequate or appropriate test requirements in the module or component certification standards.

The rest of this report focuses on the 2nd and 3rd points as well as recommendations to improve the test requirements. UL 1703 (UL, 2008) (and by extension UL 2703 [UL, 2011]) currently addresses corrosion testing by giving guidance on the type of materials that can be bonded together, and by specifying tests on ground connection samples, after which the continuity tests must be repeated.

The matrix of acceptable and unacceptable metal combinations that can be used in the grounding means is shown in the figure below (published in UL's 2007 certification requirements decision for UL 1703 [UL, 2008] and included in UL 2703 [UL, 2011]). Acceptable combinations result in combined electrochemical potentials of less than 0.6V, and are shown below the stepped cutoff line in Figure 5.

	Magnesium, magnesium alloys	Zinc, zinc alloys	80 tin/20 Zn on steel, Zn on iron or steel	Aluminium	Cd on steel	Al/Mg alloy	Mild steel	Duralumin	Lead	Cr on steel, soft solder	Cr on Ni on steel, tin on steel, 12 % Cr stainless steel	High Cr stainless steel	Copper, copper alloys	Silver solder, Austenitic stainless steel	Ni on steel	Silver	Rh on Ag on Cu, silver/gold alloy	Carbon	Gold, platinum
Magnesium, magnesium alloys	0	0.05	0.55	0.7	0.8	0.85	0.9	1.0	1.05	1.1	1.15	1.25	1.35	1.4	1.45	1.6	1.65	1.7	1.75
Zinc, zinc alloys		0	0.05	0.2	0.3	0.35	0.4	0.5	0.55	0.6	0.65	0.75	0.85	0.9	0.95	1.1	1.15	1.2	1.25
80 tin/20 Zn on steel, Zn on iron or steel			0	0.15	0.25	0.3	0.35	0.45	0.5	0.55	0.6	0.7	0.8	0.85	0.9	1.05	1.1	1.15	1.2
Aluminium				0	0.1	0.15	0.2	0.3	0.35	0.4	0.45	0.55	0.65	0.7	0.75	0.9	0.95	1.0	1.05
Cd on steel					0	0.05	0.1	0.2	0.25	0.3	0.35	0.45	0.55	0.6	0.65	0.8	0.85	0.9	0.95
Al/Mg alloy						0	0.05	0.15	0.2	0.25	0.3	0.4	0.5	0.55	0.6	0.75	0.8	0.85	0.9
Mild steel							0	0.1	0.15	0.2	0.25	0.35	0.45	0.5	0.55	0.7	0.75	0.8	0.85
Duralumin								0	0.05	0.1	0.15	0.25	0.35	0.4	0.45	0.6	0.65	0.7	0.75
Lead									0	0.05	0.1	0.2	0.3	0.35	0.4	0.55	0.6	0.65	0.7
Cr on steel, soft solder										0	0.05	0.15	0.25	0.3	0.35	0.5	0.55	0.6	0.65
Cr on Ni on steel, tin on steel, 12 % Cr stainless steel											0	0.1	0.2	0.25	0.3	0.45	0.5	0.55	0.6
High Cr stainless steel												0	0.1	0.15	0.2	0.35	0.4	0.45	0.5
Copper, copper alloys													0	0.05	0.1	0.25	0.3	0.35	0.4
Silver solder, Austenitic stainless steel														0	0.05	0.2	0.25	0.3	0.35
Ni on steel															0	0.15	0.2	0.25	0.3
Silver																0	0.05	0.1	0.15
Rh on Ag on Cu, silver/gold alloy																	0	0.05	0.1
Carbon																		0	0.05
Gold, platinum																			0

Ag Silver
Al Aluminium
Cr Chromium
Cd Cadmium
Cu Copper
Mg Magnesium
Ni Nickel
Rh Rhodium
Zn Zinc

NOTE — Corrosion due to electrochemical action between dissimilar metals which are in contact is minimized if the combined electrochemical potential is below about 0.6 V. In the table the combined electrochemical potentials are listed for a number of pairs of metals in common use; combinations above the dividing line should be avoided.

Figure 5: Electrochemical matrix of common metal combinations.

The environmental or accelerated aging tests defined in UL 1703 (UL, 2008) include:

- Section 35—Temperature Cycling Test, 200 cycles of various temperature changes from as low as minus 40 to plus 90 Celsius;
- Section 36—Humidity Test, 10 cycles of humidity-freezing; and
- Section 37—Corrosive Atmosphere testing, including salt spray test and moist carbon dioxide/sulfur dioxide test.

Some particularly poor bi-metallic connections may demonstrate problems after undergoing the humidity tests of Section 36, but most do not. The tests in Section 37 are those that are likely to lead to significant degradation of the connection, but those tests historically are only required for modules with steel frames. Because most module frames are made of aluminum, the tests are effectively optional for the broad manufacturing base.

During the past decade, a wide range of module ground connection components and methods were developed and implemented, showing mixed results in the field. To get a sense of the corrosion susceptibility of these various methods, UL performed exploratory tests during the course of the Solar ABCs study and published a paper on those findings entitled “Accelerated Aging Tests on PV Ground Connections,” (Wang et al., 2011). This paper was discussed at length and included in its entirety as an appendix to the final report published in 2012.

That discussion won’t be repeated in full here, but some of the major points from the study and the subsequent industry feedback include:

- The study objective was to investigate the long-term effectiveness of different PV grounding devices by measuring the contact resistance at the junction between the bonding devices and aluminum frames before and after exposure to simulated harsh environmental conditions.
- The bonding types included the three most common approaches (and listed methods) used today—copper wire connections via screw/washer/nut assemblies, lay-in lug assemblies, and grounding clips.
- Identical sample sets were installed and aged separately using:
    - Damp heat aging according to IEC 61215 (IEC, 2005), “Crystalline silicon terrestrial photovoltaic (PV) modules—Design qualification and type approval.” This consisted of 85°C ambient temperature and 85% relative humidity for 1,000 hours.
    - Salt-mist aging according to IEC 60068-2-11 (IEC, 1981), “Basic Environmental Testing Procedures, Part 2: Tests-Test Ka: Salt Mist.” This standard compares resistance to deterioration from salt mist between materials of similar construction, and is used to evaluate the quality and the uniformity of protective coatings. The environment consists of continuous fine mist of aerated 3% NaCl solution buffered to a pH of 5.5.
- In the damp-heat condition, the resistances for all bonding devices remained low (< 0.05 ohm) and had almost no change over 20 weeks.
- In the salt mist condition, however, most samples showed visible signs of severe corrosion and failed the ground continuity test in weeks, where resistance failure was set at > 10 ohms.

- Initial feedback included recommendations that there be additional review of the attachment methods by manufacturers of the grounding clips and lay-in lugs—small but meaningful differences in the use of washers, for example. One lay-in lug manufacturer's instructions recommend using a flat washer between any lock or star washer and the lug surface. This is presumably to prevent excessive penetration of the tin plating on the lug and exposure of the underlying copper to galvanic corrosion.
- Most stakeholders (manufacturers and other NRTLs) suggested that the tests were a welcome start, but also highly recommend additional tests with greater participation by industry to define the scope.

Although it is widely acknowledged that tests need to be more rigorous to help reduce corrosion issues, many in the industry have expressed concern about using a testing approach employing continuous exposure to salt mist. IEC 60068-2-11 (IEC, 1981) and ASTM International (ASTM) B117 (ASTM, 2011) have both been cited and used in component tests, and both prescribe continuous salt mist exposure. The general concern is that the corrosion mechanisms induced by the IEC or B117 tests are known to often differ from those found in the field, and therefore care must be taken to select the appropriate test methods. The ASTM standard itself cautions against the use of the method to predict corrosion performance in the field, particularly in sections 3.2, 3.2.1, and 3.2.2:

> *3. Significance and Use*
>
> *3.1 This practice provides a controlled corrosive environment, which produces relative corrosion resistance information for specimens of metals and coated metals exposed in a given test chamber.*
>
> *3.2 Prediction of performance in natural environments has seldom been correlated with salt spray results when used as standalone data.*
>
> *3.2.1 Correlation and extrapolation of corrosion performance based on exposure to the test environment provided by this practice are not always predictable.*
>
> *3.2.2 Correlation and extrapolation should be considered only in cases where appropriate corroborating long-term atmospheric exposures have been conducted.*

Section 3.1 is notable as well, however, for indicating that relative corrosion resistance information can be obtained from the test of specimens. Even if the UL exploratory testing raised more questions than it answered with respect to the components themselves, it did provide some useful (if not complex) information on relative improvements in performance. For example, samples using the antioxidant coating lasted longer than uncoated samples before failing, and connections that were significantly under-torqued failed much more quickly than those that used a torque wrench to achieve the manufacturer specifications. This result highlights the need to investigate more specific torque variability—to determine the failure rate difference if the connection is under-torqued a small but measurable amount, for example. Further study should also examine the impact on corrosion rate of connections that have come loose but have been re-torqued. It is important to note that over-torqueing a connection can also lead to premature failure.

RECOMMENDED APPROACH FOR IMPROVING PERFORMANCE AND CERTIFICATION

Based on the discussions so far, the recommendations from this study are:

1. Tests should be modified to better reflect the actual environmental processes seen by PV modules in the field. This is not to imply the tests can replicate the field corrosion process, because accelerated testing can never be an accurate substitute for the long-term degradation mechanisms.
2. Test results should be used to identify relative performance superiority or inferiority in the use of methods and materials, and not necessarily be considered a predictor of failure time or failure mode.
3. Manufacturers should stay informed about the bonding material pairings that are or are not demonstrating success in UL 1703 (UL, 2008) and 2703 (UL, 2011) certification tests. Although the electrochemical potential table in Figure 5 shows a very wide range of possible component combinations, it is lacking in some areas and not highly specific in others, and actual test results with alloy variations are equally informative.

Improved Test Procedures

A key recommendation is to propose UL 1703 Standards Technical Panel adoption of procedures from new IEC standards that specify salt fog and ammonia tests for PV modules.

The second edition of IEC 61701: "Salt mist corrosion testing of photovoltaic (PV) modules" was published in 2011 (IEC, 2011). The revision has significant differences from the first edition and is a substantive departure from the approach used in ASTM B117 (ASTM, 2011) and IEC 60068-2-11 (IEC, 1981). For one, its test basis is derived more from IEC 60068-2-52 (IEC, 1996), which is widely used in the electronic component field and thought to be better suited to PV module assemblies. The tests also better reflect field conditions. Most significantly, the modules are exposed to cycles of alternating salt fog followed by humidity storage under controlled temperature and relative humidity conditions. This sequence better reflects the module's corrosion processes in punishing marine environments than that of a continuous salt-fog test.

The standard also draws on IEC 60068-2-52 (IEC, 1996) by offering different levels of test severity, which are representative of different installation environments:

- One severity level is applicable to systems installed in a marine environment, with routine exposure to a wet atmosphere with dissolved salt.
- Four other severity levels are defined based on alternating exposure to salt- based and dry or humid atmospheres. One example is representative of normally dry environments where the use of salt is occasionally used to melt ice.

IEC 61701 (IEC, 2011) requires a series of performance related tests following the salt-fog exposure, among them a ground-continuity test according to IEC 61730-2 (IEC, 2004) (for crystalline silicon and thin film modules), and IEC 62108 (IEC, 2007) (for concentrating PV modules). For the purposes of the UL 1703 (UL, 2008) (and UL 2703 [UL, 2011]) standard revisions, we recommend no change to the continuity tests as currently written, only to the salt-fog test procedures in Section 36. Another recommendation is to have the test be applicable to all metal-framed modules (because current language only applies to steel frames, which—as mentioned earlier—are rarely used). Grounding hardware or assemblies can be tested and certified for a specific environment based on the severity level choice.

The IEC is also publishing IEC 62716, "Ammonia corrosion testing of photovoltaic (PV) modules," which follows closely the principles and approach taken in IEC 61701 (IEC, 2011). In IEC 62716, the tests are intended to address modules operating in highly corrosive wet atmospheres near agricultural or other industrial facilities involving concentrations of dissolved ammonia. Samples are subjected to cycles of exposure—eight hours of ammonia exposure in higher temperatures followed by 16 hours with no ammonia and lower temperatures. IEC 62716 is in final draft review by the technical committee. and will likely be published in 2013. It is recommended that this test or a similar one also be considered as an addition to the existing tests in UL 1703 (UL, 2008) and UL 2703 (UL, 2011). At this time there is no recommendation to change or remove the existing moist carbon dioxide/sulfur dioxide corrosive atmosphere test UL 1703 (Section 37.2). As in the case of the salt-fog tests, it is recommended that manufacturers have the option of choosing tests and severity levels, but in any case the listing should clearly document which environments the components have been certified to operate in.

Lessons From Field and Recent Testing Experience

Grounding devices and mounting means that have historically performed well in the field include combinations of:

- copper or a copper alloy containing not less than 80% copper, which may be coated or plated to avoid galvanic corrosion;
- stainless steel containing a minimum of 16% chromium (Cr) or 5000 or 6000 series aluminum alloys; or
- carbon steel, which may be coated or plated to avoid corrosion.

Connections that have to date shown galvanic compatibility in almost all service environments contain any combination of the following (with caveats related to sufficient thickness of platings or coatings):

- 5xxx or 6xxx series aluminum alloys and commercially pure aluminum,
- stainless steel containing a minimum of 16% Cr,
- nickel,
- tin,
- zinc, and
- zinc-aluminum alloys.

In 2012, UL experienced a surge of activity for UL 2703 (UL, 2011) grounding and bonding component certifications, and the findings with respect to different types of steel supplement the material recommendations above. Although there are occasional exceptions, the following generalizations can be made with respect to the success of bonding resistance and short-circuit tests performed after environmental conditioning:

- Components with 300 Series stainless steel have been passing well (incorporating minimum 16% Cr—austenitic chromium-nickel alloys).
- Components with 200 Series stainless steel have had mixed results (austenitic chromium-nickel-manganese alloys).
- Components with 400 Series stainless steel generally are not passing (ferritic and martensitic chromium alloys).
- Components with ASTM A690 or better galvanized steel have been successful (Atmospheric Corrosion Resistance for Use in Marine Environments).
- Components with A660 galvanized steel (and classes below) are not faring as well.
- Zinc thickness has been demonstrated to be more relevant in test results than the galvanization method (electroplating or hot-dipped). Having said that, hot-dipped galvanized steel generally fares better.

In the previous Solar ABCs reports from this study, we made the general recommendation to simplify the list of materials used for grounding devices and mounting means, based on field and industry experience. This was considered a practical alternative to defining acceptable combinations using the table in Figure 5, which by itself lacks specificity with certain alloys and does not provide sufficient guidance for the determination of electrochemical potentials.. However, it is not our intent to impose restrictions on the use of alternate materials in the standards. The standards should identify functional requirements but not limit creativity or innovation with respect to materials and combinations. In order to realize this, however, new requirements and tests need to be developed and proposed to revise the standard. UL is currently in the process of creating a new expanded table and procedure for determining acceptable metal combinations. This will incorporate information gained from the ongoing UL 2703 component testing described earlier, but will also document a more detailed process for measuring the electrochemical potential so that a consistent approach can be used to test metals not included in the table. The important outcome is the long-term performance and integrity of the electrical connections once subjected to the accelerated aging and corrosion tests, and their subsequent performance in the field.

CONCLUSIONS AND NEXT STEPS

This report provides a brief update on findings related to module and ground component corrosion, and presents recommendations to adopt revised accelerated aging test procedures recently published by the IEC. UL 2703 (UL, 2011) certification testing at UL and other NRTLs is providing valuable information on the performance of various steels and alloys under accelerated aging conditions. We expect that there will also be plenty of new valuable information from manufacturers and test labs during the next few years that will help set the direction for improved component designs and testing. With this in mind, important next steps for the industry include:

- The Standard Technical Panels for UL 1703 (UL, 2008) and UL 2703 (UL, 2011) should review the IEC standard procedures outlined in this report. Possible outcomes are formal adoption of the IEC standards as U.S. ANSI standards or adoption of similar test procedures in the next revision of UL 1703 and UL 2703.
- Expanded exploratory testing building on the tests performed by UL in Taiwan is encouraged to address recommendations and feedback coming from the industry.
- A forum similar to Solar ABCs should continue to help consolidate and circulate information from the field and from various stakeholders working on corrosion analysis and mitigation.

ACRONYMS

ANSI	American National Standards Institute
ASTM	Formerly American Society for Testing and Materials, now ASTM International
Cr	chromium
IEC	International Electrotechnical Commission
IECEE	IEC System of Conformity Assessment Schemes for Electrotechnical Equipment and Components
IEEE	Institute of Electrical and Electronics Engineers
NEC	*National Electrical Code*
NFPA	National Fire Protection Association
NRTL	Nationally Recognized Testing Laboratory
PV	photovoltaic
UL	Underwriters Laboratories

REFERENCES

ASTM International (ASTM). (2011). *Standard practice for operating salt spray (fog) apparatus*. ASTM B117-11.

International Electrotechnical Commission (IEC). (1981). *Basic environmental testing procedures, Part 2: Tests. Test Ka: Salt mist*. 60068-2-11 (Ed. 3).

IEC. (1996). *Environmental testing—Part 2: Tests—Test Kb: Salt mist, cyclic (sodium, chloride solution)*. 60068-2-52 (Ed. 2).

IEC. (2004). *Photovoltaic (PV) module safety qualification—Part 2: Requirements for testing*. IEC 61730-2 (Ed. 1).

IEC. (2005). *Crystalline silicon terrestrial photovoltaic (PV) modules—Design qualification and type approval*. 61215 (Ed. 2).

IEC. (2007). *Concentrator photovoltaic (CPV) modules and assemblies—Design qualification and type approval*. 62108 (Ed. 1).

IEC. (2011). *Salt mist corrosion testing of photovoltaic (PV) modules*. 61701 (Ed. 2).

IEC. (2013, pending publication). *Ammonia corrosion testing of photovoltaic (PV) modules*. 62716 (Ed. 1).

National Fire Protection Association (NFPA). (2011). *National Electrical Code*. NFPA 70.

UL. (March 15, 2002, including revisions through April 2008). *UL standard for flat-plate photovoltaic modules and panels*. UL 1703. Third Edition.

UL. (2011). *UL standard for rack mounting systems and clamping devices for flat-plate photovoltaic modules and panels*. UL 2703. First Edition.

Wang, E. (Ethan), Yen, K. (Kai-Hsiang), Wang, C. (Carl), Ji, L. (Liang), and Zgonena, T. (Timothy). (June 2011). "Accelerated aging tests on PV grounding connections." Underwriters Laboratories. Presented at the IEEE 37th Photovoltaic Specialist Conference.

RESOURCES

International Electrotechnical Commission (IEC). (July 13, 2005). Effects of current on human beings and livestock. Part 1: General aspects, Edition 4.0. IEC/TS 60479-1.

National Physical Laboratory. (2000). "Bimetallic corrosion: Guides to good practice in corrosion control." United Kingdom (UK). Publication of the UK Department of Trade and Industry.

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