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ELECTRICAL SAFETY REQUIREMENTS: IMPLICATIONS FOR THE MODULE DESIGNER

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ABSTRACT

Commercial photovoltaic array installations, which include residential and intermediate applications, are subject to building and electrical codes and to product safety standards. The National Electrical Code (NEC) Article 690, titled "Solar Photovoltaic Systems," contains provisions defining acceptable levels of system safety and emphasizes the system design and its installation. The Underwriters Laboratories, Inc. (UL), document titled Proposed First Edition of the Standard for Flat-Plate Photovoltaic Modules and Panels, UL-1703, identifies module and panel construction requirements that ensure product safety. Together these documents describe requirements intended to minimize hazards such as shock and fire. Although initial focus of these requirements is on single-crystal silicon modules, they are generic in nature, and are equally applicable to high-voltage (>30 Vdc), multi-kilowatt, thin-film systems.

A major safety concern is insulation breakdowns within the module or array wiring system, or discontinuities within the electrical conductors. These failures can result in ground faults, in-circuit arcs, or exposure to hazardous electrical parts. Safety issues include:

Allowable construction practices: material temperature limitations, ampacity of current-carrying parts, compatibility of connection means with recognized wiring systems, spacing between uninsulated live parts, wiring compartment volume and construction, metallic coating thickness, edge sharpness, accessibility of live parts, and markings.

Electrical insulation system integrity and grounding requirements: leakage current levels, bonding path resistance, dielectric voltage withstand, inverse current overload, and continuity of grounding connection.

Environmental durability: pull test for leads or cables, push test, cut test, terminal torque test, impact test, exposure to water spray test, accelerated aging of gaskets and seals, temperature cycling test, humidity test, corrosive atmosphere test, hot-spot endurance test, flammability test, and mechanical loading test.

As in other electrical systems, safeguards that address these issues may be incorporated in the module, the installation, or both. These safety-related features are evaluated at the system level in terms of compliance with electrical codes, and at the component (module) level in terms of satisfying product safety standards. This overview presentation is intended to provide a basic understanding of the electrical safety implications for the module designer of thin-film modules.

INTRODUCTION

The objective of this presentation is to provide a summary of safety requirements for thin-film modules intended for use in high-voltage (30 Vdc) systems. The focus is a basic understanding of the electrical safety implications for the designer of thin-film modules. The basis for examining appropriate safety design practices consists of two documents: the 1984 National Electrical Code (NEC) Article 690, "Solar Photovoltaic Systems" (Reference 1), which addresses safety issues at the system level, including system design and installation, and the unique characteristics of photovoltaic systems that could result in an unsafe installation; and the Underwriters Laboratories, Inc. (UL) document Proposed First Edition of the Standard for Flat-Plate Photovoltaic Modules and Panels, UL1703 (Reference 2), which addresses construction practices and electrical safety requirements at the module level, including product safety as related to the factory-built item.

SYSTEM SAFETY CONCERNS

Certain unique electrical characteristics have resulted in the 1984 NEC addressing photovoltaics in a separate article. Since full system voltage is present at very low illumination levels, a shock hazard is present at all times, and unlike conventional power sources that can be turned off, the array is always "hot." This is illustrated in Figure 1, showing that the maximum open-circuit voltage exists even at very low levels of illumination. Additionally, since the short-circuit current is limited, the operation of overcurrent safety devices may be impaired. Note, in the same figure, that the short-circuit current is a function of illumination level, unlike conventional power sources that typically have infinite short-circuit current.

As in most electrical equipment, the identification of safety requirements begins at the system level with overall safety concerns that include: (1) protection of personnel and the prevention of electrical shock hazards; (2) protection of equipment by minimizing electrical stresses in the event of ground faults; and (3) protection against fire hazards from internally generated sources, such as overheated parts or arcing, and from externally generated sources, such as burning brands or the spread of flames.

The array safety philosophy is based on the concept of safety in depth: a primary protection scheme together with a number of redundant protection schemes that are compatible with the overall photovoltaic system design. The primary protection consists of the module and wiring insulation that isolates electrically active parts of the equipment and cables. In addition, several secondary protection schemes are employed, each independent of the primary scheme both in design and in function. Frame grounding, circuit grounding, ground-fault detection, and blocking diodes and overcurrent devices are typical examples of secondary schemes. The key element of this philosophy is that a single failure should not render both primary and backup schemes inoperable.

ISOLATION AND GROUNDING SAFETY CONCEPTS

Figure 2 represents an example of a photovoltaic system that incorporates this safety-in-depth philosophy. The diagram shows two parallel source circuits consisting of series-connected modules, each module mounted in a conductive frame. The module frames are bonded together and permanently attached to the frame structure ground in such a way that removal of a single module does not affect the integrity of the bonding path. Each source circuit has in series both a blocking diode and an overcurrent device (in this example, a fuse). One of the circuit conductors is grounded and the array circuit incorporates a ground-fault-detection system. The photovoltaic array is connected to a power conditioner (PC), whose case is grounded. The output of the PC is then connected to the load.

In the event of an insulation failure, each of the secondary protection schemes provides an additional, independent measure of protection.

Frame Grounding:

Protects against shock hazards associated with module frame members that have become energized by failure of the primary insulation system. It does not protect against direct contact with the circuit conductors.

The approach is to provide a low-resistance path to ground to conduct fault current and to maintain frames at close to ground potential (below shock hazard level: ≥30 Vdc and 1 mA).

Circuit Grounding:

Protects against excessive voltage stress on the primary insulation system. It also enables shock hazard protection if combined with a ground-fault-detection system.

The approach is to prevent the source circuit from floating to a high voltage with respect to ground by solidly grounding one of the array circuit conductors. Alternative approaches include: a center-tap ground that limits the maximum voltage stress to one-half the output voltage of the source circuit; or a resistance-to-ground that limits ground-fault currents to a safe value.

Ground-Fault Detection:

Protects against shock hazards associated with personal contact with system conductors. It may be used to protect equipment in conditions associated with arcing between system conductors and ground.

The approach is to install a sensor (such as a Hall effect device) that detects a current imbalance in the circuit conductors. An alternative approach is to sense the voltage drop across a resistor situated in the circuit ground path.

Blocking Diode and Overcurrent Device:

Protects against reverse current through modules during fault conditions.

The approach is to install a blocking diode to prevent other parallel source-circuit currents from entering the faulted source circuit. The overcurrent device, a fuse, provides additional protection in case of a shorted diode.

The purpose of this example is to illustrate that the module design must be compatible with the overall safety system configuration. For example, the module voltage-isolation capability is constrained by the system voltage, and not by the module voltage. In the source circuits shown in Figure 2, the modules physically connected near the circuit ground will experience voltage stresses equal to their module voltage, whereas the modules located near the blocking diode will experience voltage stresses equal to the system voltage, which could be many times higher than the module voltage. Additionally, it can be seen that the module reverse-current capability requirement is a function of the series fuse rating and not the short-circuit current of the module.

MODULE ELECTRICAL INSULATION SYSTEM INTEGRITY AND GROUNDING REQUIREMENTS

Based on this need for compatibility between the module and the system configuration, product safety standard UL 1703 sets forth module and panel construction practices and electrical requirements to ensure product safety for the factory-built item. For convenience in presentation, the requirements have been classified into three categories. Figure 3 identifies major module electrical insulation system integrity and grounding requirements; Figure 4 highlights the details of specific module electrical insulation and grounding tests. Note that for system voltages equal to or greater than 30 Vdc, the test voltage for the module-isolation capability requirement is equal to two times the system voltage plus 1000 Vdc.

MODULE SAFETY COMPONENT DURABILITY TESTS

Figure 5 summarizes module safety component durability tests that are based on the expected use environment. Many of these requirements are based on conditions encountered during handling, packing, and transporting of modules to the installation site. For example, the strain relief test for leads and cables is a test of the attachment means, consisting of a 20-pound force applied for one minute in any direction, without damaging the lead or cable, its connecting means, or the module or panel. The ARCO Gemini module experienced no difficulty in passing this test. As another example, the impact test consists of dropping a 2-inch-diameter steel ball, weighing 1.18 pounds, onto the most vulnerable part of the module from a height of 51 inches. The criteria for passing this test is that there are no accessible live parts, or shards of glass larger than 1 square inch. Although the glass superstrate of an ARCO Gemini module cracked when subjected to this test, the 1/8 inch glass substrate remained intact. Since there were no accessible live parts, or shards of glass larger than 1 square inch, as shown in Figure 6, the module is considered to have passed this test.

MODULE CONSTRUCTION PRACTICES AND MATERIALS

Finally, required module construction practices and materials, summarized in Figure 7, identify basic, good engineering design practices applicable to photovoltaic modules. For example, compatibility of connection means with recognized wiring systems refers to NEC provisions that identify acceptable terminals, connectors, or pigtail leads (with a minimum free length of 6 inches).

MODULE FLAMMABILITY TESTING: MANUFACTURER'S OPTION

The last topic to be addressed is module flammability testing, an optional test performed at the manufacturer's request. Module flammability involves three distinct risk areas: (1) the ability of a module to self-ignite due to an electrical arc; (2) the susceptibility of a module to ignition from an external flame source; and (3) the extent to which an array affects the flammability of a fire-sensitive application. The last two items are a major consideration for fire-rated applications, such as roof-mounted photovoltaic arrays on public buildings and in certain residential communities with a high fire concern. Three specific fire-resistance ratings have been defined: Class A, effective against severe fire exposure; Class B, effective against moderate fire exposure; and Class C, effective against light fire exposure. UL 1703 has identified two tests from another safety standard, Tests for Fire Resistance of Roof Covering Materials, UL 790 (Reference 3), as applicable to photovoltaic modules. The spread-of-flame test is designed to measure resistance to flame spread due to an external source of flame impinging on the top surface of a photovoltaic array. The burning-brand test measures the ability of an array to resist penetration due to burning brands. Figure 8 summarizes the principal parameters of each test. Findings indicate that most EVA modules will barely qualify for a Class C fire rating, and that special materials and constructions are required for Class B and Class A fire ratings (References 4 and 5). During or after these tests, the modules are not required to be operational. (Over the past two years the Jet Propulsion Laboratory has done extensive work in the area of module flammability. Additional information can be obtained from the author.)

SUMMARY

The summary, Figure 9, focuses on two points: for systems designed to operate at above 30 Vdc, electrical safeguards must be incorporated in the module, the installation, or both; and for intended operation in fire-sensitive installations, optional module flammability tests determine the fire classification.

ACKNOWLEDGMENTS

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REFERENCES

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2. Proposed Edition of the Standard for Flat-Plate Photovoltaic Modules and Panels, UL 1703, Underwriters Laboratories, Inc., Northbrook, Illinois, September, 1984.

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4. Sugimura, R.S., et al, "Flammability of Photovoltaic Modules," Proceedings of the 17th IEEE Photovoltaics Specialists Conference, Orlando, Florida, May 1-4, 1984, pp. 489-495, Institute of Electrical and Electronics Engineers, Inc., New York, 1984.

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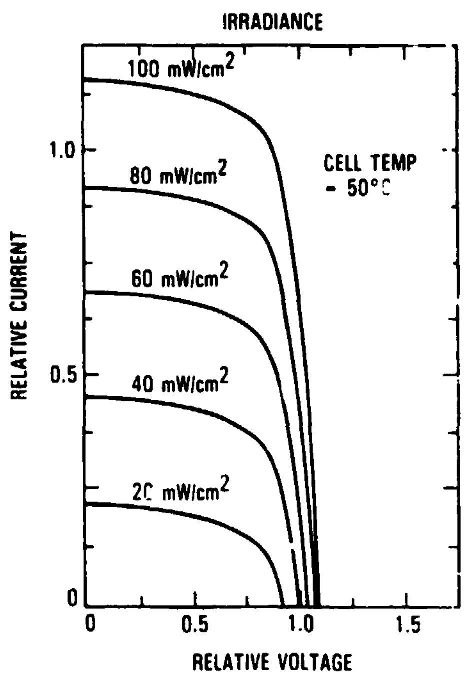
Figure 1. Unique Photovoltaic Electrical Characteristics



- Array is always "on"
- Voltage present at very low illumination — shock hazard exists at early morning & late evening
- Current proportional to illumination
- Short-circuit current is limited — may affect operation of overcurrent devices

Figure 2. Isolation and Grounding Safety Concepts

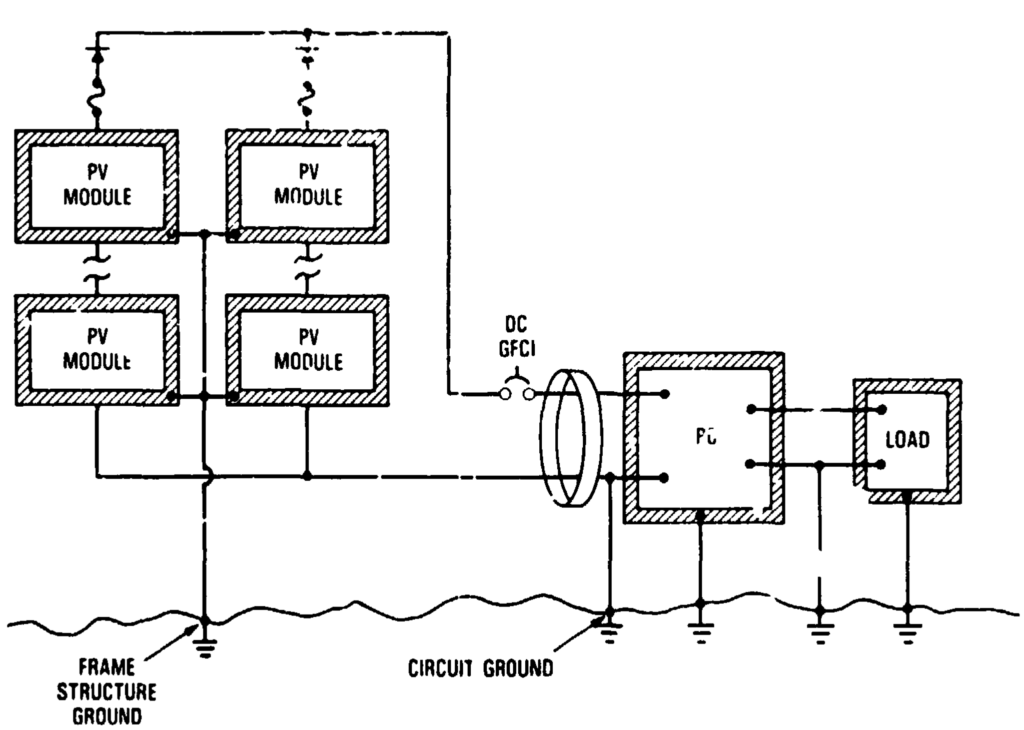


Figure 3. Module Electrical Insulation Svstem Integrity and Grounding Req...rements

- **Dielectric voltage withstand (cell string to frame)**
- **Maximum allowable leakage current (cell string to frame)**
- **Maximum allowable bonding resistance in the ground path**
- **Tolerance to inverse current overload**
- **No acce sible live parts**
- **Minimum spacing between conductors**
- **Maximum allowable temperatures for polymeric materials**

Figure 4. Module Electrical Insulation and Gro... ..ing Tests

Test	Test Level	Conditions	Acceptance Criteria
Dielectric voltage withstand (cell string to frame)	500 Vdc fc· systems<30 Vdc; 2 x system voltage + 1000 Vdc	Dry, ·fter water spray, temperature cycled, humidity tested, and exposed to corrosive atmosphere	Leakage current: $\leq 50\ \mu A$
Leakage current levels (cell string tc frame or insulating su···es)	Rated maximum system voltage	Dry and after water spray	Leakage current: $\leq 10\ \mu A$ cell string to frame; ≤ 1 mA cell string to insulating surfaces
Bonding resistance in the ground path	Current: twice the rating of the series fuse	Dry	Resistance: ≤ 0.1 ohm
Inverse current overload	Reverse current: 1.35 x rating of the series fuse	Dry	No flaming of cheese clo·h or tissue paper

Figure 5. Module Safety Component Durability Tests

- **Temperature cycling test**
- **Humidity test**
- **Hot-spot heating test**
- **Impact test**
- **Terminal torque test**
- **Mechanical loading test**
- **Strain relief test for leads and cables**
- **Push test**
- **Cut test**
- **Accelerated aging of gaskets and seals**
- **Corrosive atmosphere test**

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Figure 6. ARCO Gemini Module After Impact Test

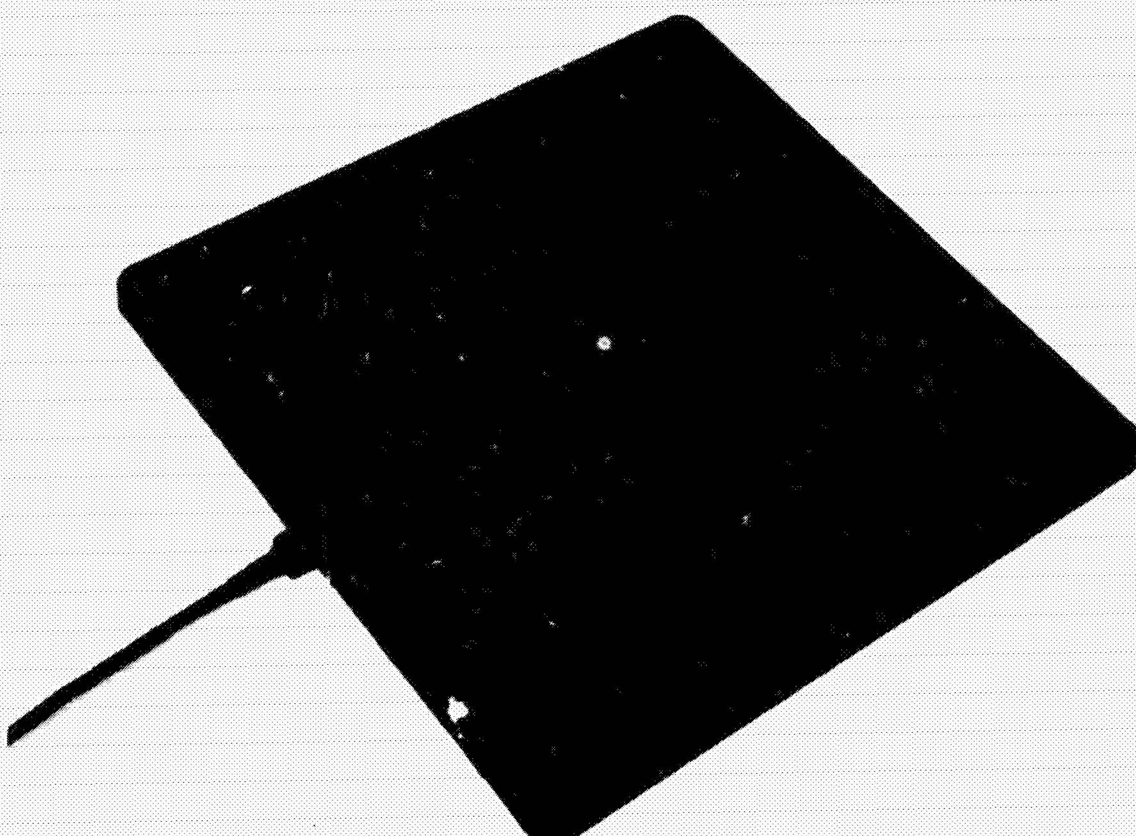

Figure 7. Required Module Construction Practices and Materials

- Compatibility of connection means with recognized wiring systems
- Wiring compartment volume and construction
- Metallic coating thickness
- Edge sharpness limitations
- Markings

Figure 8. Module Flammability Testing: Manufacturer's Option

- **Tests for Fire Resistance of Roof Covering Materials, UL-790**
  - **Spread-of-flame test — distance that flame has spread; no flaming or glowing brands of roof material**
  - **Burning-brand test — until flame, glow and smoke disappear; no sustained flaming on underside, production of flaming or glowing brands of roof material**

Fire Rating	Spread-of-Flame Test			Burning-Brand Test		
	Flame Temperature, °F	Flame Application Time, min	Allowable Flame Spread Distance, ft.	Brand Size, in.	Brand Ignition Temperature, °F	Approximate Peak Module Temperature, °F
Class A	1400	10	≤ 6	12 x 12 x 2¼	1630	1900
Class B	1400	10	≤ 8	6 x 6 x 2¼	1630	1400
Class C	1300	4	≤13	1½ x 1½ x 25/32	–	–

- Most EVA modules will barely qualify for a Class C fire rating
- Special materials and constructions are required for Class B and Class A fire ratings

Figure 9. Summary

- Electrical safeguards must be incorporated in the module, the installation, or both, for systems designed to operate at above 30 Vdc
  - Evaluation at the module level — conformance to product safety standards: Proposed First Edition of the Standard for Flat-Plate Photovoltaic Modules and Panels, UL-1703
  - Evaluation at the system level — compliance with electrical codes: 1984 NEC Article 690, Solar Photovoltaic Systems
- For intended operation in fire-sensitive installations, optional module module flammability tests determine the fire classification — Tests for Fire Resistance of Roof Covering Materials, UL-790
  - Burning-brand test
  - Spread-of-flame test

DISCUSSION

ARNETT: I think it might be a good idea to clarify, for those system designers who happen to come to this conference, how you specify what the system voltage is. Most of us who are system designers think of system voltage as the voltage point at which you get your maximum power out of the system, in which you tend to operate. For purposes of safety I believe there is a different way in which that is specified.

SUGIMURA: Yes. That's taking a module at 100 mW/cm^2, 0^oC, and open circuit. The number of modules that are in a source circuit are then added up to come up with that system voltage.

HARTMAN: Has any determination been made -- if you have an isolated frame material, hardware -- if that should be grounded or not? I might have missed it if you talked at it at the beginning.

SUGIMURA: Are you talking about a polymeric frame, perhaps with metal screws or metal fasteners?

HARTMAN: On a metal structure, what should be grounded?

SIGUMURA: A metal structure will definitely have to be grounded. You are talking about a ground-mounted array, to meet National Electrical Code requirements you will have to ground that metal structure. If you are talking about a polymeric frame using metal screws that are going into a wood substructure, I think it is a matter of whether or not UL feels that those metallic screws or fasteners could somehow become energized. Whether that becomes 1 in. or 1/2 in. is basically up to them. In discussions with Underwriters Laboratories, they might be able to give you some guidelines on what they consider at the present time to be safe.

VAN LEEUWEN: On the viewgraphs you had up, delineating all of the tests that UL applies to modules, the bottom of the list was corrosive environment. I believe I heard you say that aluminum, stainless steel and polymeric materials are not subjected to this test?

SUGIMURA: They are excepted from those tests, per the standard. This was as of March 1984.

VAN LEEUWEN: So all that's left is the glass? If you don't have aluminum, stainless steel or polymeric materials -- are they accepted or excepted?

SUGIMURA: They are excepted from the test. The test is not performed if you have a glass module with those particular components on it.

VAN LEEUWEN: So what type of modules are there that --

SIGUMURA: Well, if you were to use a sheet-steel frame or a metallic frame that was not properly protected, they would go ahead and perform the corrosive atmosphere test. I am not aware of modules that they have performed this test on, it was just that when they set out to establish these requirements, they tried to consider all possible configurations of a photovoltaic module.

TRENCHARD: In deploying our modules we have a lot of problems with people getting their hands cut on these things. I have not been able to find a good specification for preventing that or to build into the design. Do you happen know if there is a standard for that?

SUGIMURA: For what? Sharpness? I think UL does have it in that 1703. I don't remember the name of the UL standard that addresses that situation, but there is one. I'll check with you after the program.