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SAFETY REQUIREMENTS FOR WIRING SYSTEMS AND CONNECTORS  
FOR PHOTOVOLTAIC SYSTEMS

JPL CONTRACT NO. 955392

FLAT-PLATE SOLAR ARRAY PROJECT  
RELIABILITY AND ENGINEERING SCIENCES AREA

FINAL REPORT

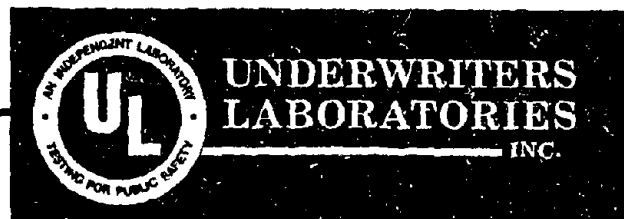
September, 1984

Prepared For

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The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of flat-plate solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

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- 3 -

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ABSTRACT

Safety requirements for wiring systems and connections and for separable connectors for use in roof-mounted photovoltaic (PV) arrays are identified. These requirements were established by considering the environmental use-conditions applicable to PV arrays and the differences between integral-, direct-, standoff- and rack-mounted modules.

The articles in the National Electrical Code (NEC) covering wiring systems are discussed to: (1) define the wiring systems, (2) identify the permitted uses and use-restrictions, (3) outline the advantages and disadvantages and (4) address the concerns regarding support, protection against mechanical damage and wet versus dry locations. An overall assessment is made of the advantages and disadvantages of each wiring system to arrive at candidate wiring systems that are best suited for use in PV arrays. For candidate wiring systems having use-restrictions that may prohibit their use, considerations are given that need to be addressed by any proposed revision to the National Electrical Code to permit acceptance by the inspection authorities.

The various wiring termination methods that are permitted by the NEC are discussed and those which have features that are desirable for PV applications are identified.

Performance and construction requirements for PV cable and for PV connectors are presented in separate outlines of proposed investigations of these products.

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## 1. INTRODUCTION

Because solar terrestrial photovoltaic (PV) systems represent a comparatively new technology, extensive field experience and records of tests are not presently available identifying safety performance of wiring systems and connectors used in PV applications. Consequently, present codes and standards do not contain detailed requirements for wiring systems and connectors specifically intended for use in PV applications. This Report identifies those wiring systems described in the National Electrical Code, NEC\* that are considered to be candidate PV wiring systems, and discusses considerations that need to be addressed to qualify them for use in PV applications. In addition, this Report outlines safety requirements that can be used in the evaluation of PV cable and connections that are specifically intended for PV applications. It is intended that the discussions and requirements contained in this Report will assist designers, manufacturers, installers and inspection authorities in promoting cost-effective and safe installations of PV systems.

Other recently available documents covering safety requirements for PV applications include: (1) NEC Article 690-Solar PV Systems; (2) Underwriters Laboratories Inc., proposed Standard For Safety-Flat Plate Photovoltaic Modules and Panels; (3) DOE/JPL 955392-2, Safety-Related Requirements For PV Modules and Arrays; and (4) Draft Standard For Safety-Power Conditioning Units For Use In Residential Photovoltaic Power Systems, September, 1982.

The NEC provisions for wiring methods covered in Sec. 690-31 permits all raceway and cable wiring methods included in the Code to be used in PV installations. The applicability of these wiring systems relative to PV use are discussed. Sec. 690-31 also permits other wiring systems specifically intended and identified for use in PV arrays. The discussions contained in this Report on candidate wiring systems and the requirements for PV cable are intended to serve as guidelines to designers and manufacturer's in producing wiring systems specifically intended for PV applications.

\* - National Electrical Code (R) and NEC (R) are Registered Trademarks of the National Fire Protection Association, Inc., Quincy, Massachusetts.

Sec. 690-32 of the NEC permits the use of separable connectors for connections of modules. The general requirements for such connectors covering configurations, guarding, type, grounding and ratings are contained in Sec. 690-33 of the NEC. This Report contains detailed safety requirements covering construction and performance for PV connectors intended to be used in accordance with Secs. 690-32 and 33 of the NEC. Presently available Listed PV connectors have been investigated and found to comply with these requirements.

## 2. OBJECTIVES

The objectives of this Report are to (a) identify and define intermodule and array wiring and cable systems that are consistent with safety requirements, (b) generate detailed requirements and detailed conceptual designs for wiring systems for roof-mounted PV arrays, (c) document these requirements and detailed conceptual designs in a form suitable for consideration and trial use by the photovoltaic community.

The following aspects were considered:

- A. Module operating environment such as wet versus dry locations; temperature constraints; and the differences between standoff, rack, direct and integral arrays.
- B. Hardware elements, such as wire/cable insulation types, wire/cable interfaces of modules, panels, and auxiliary devices (blocking diodes, bypass diodes, ground-fault detectors, etc.)
- C. System safety such as identified in the National Electrical Code, (NEC), Article 690, (1984 Edition), and DOE/JPL 955392-2, Safety-Related Requirements for Photovoltaic Modules and Arrays.

## 3. BACKGROUND

For the purpose of this Report, a PV wiring system is considered to include all wiring from the module interconnections to the interface with the utility system at the electrical service equipment of the premises. The discussion covers wiring and connections: (1) between the modules, and from modules to the common connection point(s) of the direct-current system, i.e. the PV source circuits, (2) from the common connection point(s) to the power conditioning unit, i.e. the PV output circuit and, (3) to the power conditioning unit output circuit or direct-current utilization equipment. This material also applies to wiring that may be present for connection of additional equipment, such as L-C filter assemblies, lightning protection devices and fault-current detectors. (The terms PV source circuit and PV output circuit are defined in Article 690 of the NEC.)

In descriptions of various wiring systems, there are a number of terms whose meanings may be commonly understood. However, because different interpretations may be encountered, the following definitions are given, for purposes of this document, together with the source of information, where applicable.

Cable - A cable may have a single conductor or a combination of conductors insulated from one another (multiple-conductor cable). The component conductors of a cable may be either solid or stranded. Multiple conductor cable may or may not have a common insulating covering.

(Standard Handbook For Electrical Engineers, 11th Edition, Donald Fink, Editor In Chief, H. Wayne Beaty, Associate Editor, McGraw-Hill Book Company.)

Conductor -

Bare - A conductor having no covering or electrical insulation whatsoever. (See "Conductor, Covered".)

Covered - A conductor encased within material of composition or thickness that is not recognized by the National Electrical Code (NEC) as electrical insulation. (See "Conductor, Bare.")

Insulated - A conductor encased within material of composition and thickness that is recognized by the NEC as electrical insulation.

(National Electrical Code, 1984 Edition, National Fire Protection Association.)

Connector - A device permanently connected (affixed) to cable or cord and intended for plug-in connection to a mating connector which is permanently mounted to a fixed part or permanently connected (affixed) to another cable or cord. Separation of the mating connectors may be accomplished with or without the use of a tool.

Cord - A small cable, very flexible and substantially insulated to withstand wear. There is no sharp dividing line in the respect to size between a cord and a cable and likewise no sharp dividing line in respect to the character of insulation between the cord and a stranded wire.

Raceway - An enclosed channel designed expressly for holding wires, cables, or busbars, with additional functions as permitted in the NEC.

Explanatory Note: Raceways may be of metal or insulating material, and the term includes rigid metal conduit, rigid nonmetallic conduit, intermediate metal conduit, liquidtight flexible metal conduit, flexible metallic tubing, flexible metal conduit, electrical metallic tubing, underfloor raceways, cellular concrete floor raceways, cellular metal floor raceways, surface raceways, wireways, and busways.

(For definition and explanatory note, same source as for "Conductor".)

Splice - Connection point of one conductor to one or more other conductors.

Terminal - Connection point of one or more conductors to a fixed part.

The National Electrical Code contains a number of articles which include requirements on various types of cables and flexible cords. In general, each of these articles treats the wiring method presented as a system. Addressed are the construction of the system, uses permitted, uses not permitted, installation methods and other special considerations as may be applicable. Single conductors are only permitted to be installed where part of a recognized wiring method contained in Chapter 3 of the NEC.

A review of earlier editions of the NEC shows that new wiring systems have been added to the Code over the years. Each new system had a set of specific uses and a set of limitations. The reasons for the limitations or the permitted applications may no longer be self evident. The following paragraphs may explain the reasons for this condition.

The development process for NEC revisions covering a new wiring system may be initiated when a manufacturer develops a new product or system which has some desirable attributes and which is believed to be equivalent to established systems in the level to which risks of electric shock, fire or injury to persons are reduced. These beliefs generally are demonstrated by a fact-finding investigation which is used to support the proposed Code revisions and additions covering the installation of the system. The fact-finding investigation may reveal some weaknesses in the system or some aspects involved in use of the system may not have been addressed, by choice or otherwise. These may result in use limitations in the NEC proposals on the new system. Also, it may have been perceived by the supporters of the proposed system that its acceptance may be enhanced if the system is limited to a narrower range of applications. The reasons for the limitations may have become obscured with the passage of time, nevertheless limitations do exist and they should be reviewed when a particular system is considered for use, because the inspection authorities are obligated to apply them.

Proposals for revisions or for new material in the NEC, the substantiating statements and the action of the Code Making Panel on each proposal, are contained in the National Electrical Code Technical Committee Report, (Preprint of the Proposed Amendments for the NEC), which is issued for the purpose of obtaining public comments. The background and reasons for the limitations for the NEC requirements is likely to be contained in the "Preprint" of the Code Cycle during which the requirements were adopted. It is possible that this information can be retrieved by interested readers from technical libraries and the NEPA library located in Batterymach Park, Quincy, MA 02269. This process may be expedited by contacting the chairman of the appropriate Code Making Panel to determine approximately when a particular requirement was adopted.

#### 4. REQUIREMENTS FOR PHOTOVOLTAIC WIRING SYSTEMS

The appropriate requirements for wiring systems employed in PV arrays are presented in the following paragraphs. These requirements are based on the following important points pertinent to PV arrays: (1) The environmental and use considerations; (2) a concern to provide for ease of installation, inspection and maintenance; and (3) possible means for disablement of the array in accordance with the provisions contained in Sec. 690-18 of the NEC (1984).

Regarding the environmental and use considerations for PV wiring systems, the following conditions were addressed: (1) exposure of the wiring to moisture, rain and sunlight; (2) exposure of the wiring to physical damage; and, (3) appropriate cable support. The effect of these conditions on the wiring system depends on the various PV module mounting methods employed, which include: integral-, direct-, standoff- and rack-type mounts. The following paragraphs point out features of each of these mounting methods that are relevant to the wiring system and provide some guidelines for addressing the environmental and use considerations which pertain to PV arrays.

Unless otherwise stated, the article and section references given below pertain to the National Electrical Code, (1984).

#### 4.1 Integral Mount

Integral-mounted PV modules are secured to a metal framework assembly which is supported by the roof rafters without the roof sheathing. The necessary gaskets or sealing materials are employed so that the installed panels provide a watertight exposed surface. Module interconnecting wiring is contained within the building. Accordingly, all of the wiring systems covered in Chapter 3 of the NEC are applicable within the use-conditions specified in the individual Articles. The methods for providing protection against physical damage and for providing support for these wiring systems are described in the NEC and are applicable to PV arrays containing integral-mounted modules. For example, if nonmetallic-sheathed cable (Type NM) is employed and if it is located in an accessible attic, protection against physical damage in accordance with the provisions contained in Sections 336-9 and 333-12 applies. These Sections specify that guard strips are necessary to protect NM Cable run across the top of attic floor joists or across the face of rafters or studding within 7 ft. of the attic floor or floor joists.

The provisions covering support of Type NM Cable are contained in Sec. 336-5 which states that the cable is to be secured by staples, straps, or similar fittings at intervals not exceeding 4-1/2 ft. and within 12 in. from each junction box. (Some exceptions to the dimensions apply in special constructions).

Since the wiring for integral-mounted modules is contained within the building, the conductors are protected from weather and moisture. Therefore, conductors rated for only dry locations may be employed and they need not be sunlight resistant. Also, junction boxes containing terminals or splices for module interconnect wiring do not need to be weatherproof.

#### 4.2 Direct Mount

Direct-mounted modules are installed directly over an unfinished roof deck or the finished roof without a clearance between the back side of the modules and the roof. In most installations, the exposed surface of the completed array is the watertight membrane of the structure. Module interconnecting wiring is located between the roof and the module or in channels between modules. Some of the constructions observed employ a flat conductor cable wiring system.

The location of the wiring system employed in an array having direct-mounted modules may generally be considered as damp. If the exposed surface of the array is watertight and the wiring system is between the array and the roof, it would be exposed to only a moderate degree of moisture and therefore the location would be considered as damp. On the other hand, if the wiring system is in channels that are not watertight, the wiring system may be exposed to direct rain, run-off water and wind driven snow. This would be considered a wet location. In either case, the conductors contained within raceways should be suitable for wet locations. Such conductors are identified by the letter "W" specified in the conductor type designation such as "THW", "THWN" and "RHW".

Cables employed in an array having direct-mounted modules which do not have a watertight exposed surface should be suitable for wet locations, such as Type UF Cable. On the other hand cables which are suitable for damp locations such as Type NMC may be employed in an array having direct-mounted modules having a watertight exposed surface.

Raceways employed in an array having direct-mounted modules which do not have a watertight exposed surface should be made watertight and suitably drained. For example, liquidtight flexible conduit or electrical metallic tubing used with raintight fittings could be employed. If the exposed surface of the array is watertight, raceways need not be watertight.

When wiring systems employed for interconnection of direct-mounted modules are protected from exposure to sunlight, the conductors need not be sunlight resistant.

Where the wiring is located underneath the modules, the intermodule connections can be accomplished by connectors which are an integral part of the module. The module and connector assembly is designed so that connections are accomplished when the module is mounted and secured in place. If the exposed surface of the array is not watertight, the connectors should be resistant to the effects of water and moisture. Module constructions with channels generally use interconnection between integral module wiring leads.

The roof or deck can serve as the support of the module interconnecting wiring. Protection of this wiring from physical damage is provided by the module and roof or deck.

#### 4.3 Standoff Mount

Standoff-mounted modules are supported by a mounting frame assembly which provides a clearance space between the modules and the roof. The exposed surface of the array may or may not be watertight.

Module interconnect wiring is contained within the clearance space between the modules and the roof. Since the modules are usually mounted close to the roof, this space is inaccessible and therefore, the wiring can be considered to be a location which protects the conductors from physical damage. Accordingly, for this wiring, it is not necessary to apply the provisions contained in the NEC covering protection of conductors from physical damage. Also, if the wiring is protected from exposure to sunlight, the wiring does not need to be sunlight resistant.

Although the exposed top surface of the array may be watertight, the area between the roof and the perimeter of the array is generally open. Since this construction will allow water run-off and wind driven rain or snow to enter the space between the roof and the array where the wiring system is located, wet-rated conductors should be employed.

Cables used for module interconnection should be suitably supported in accordance with the methods specified in the appropriate articles contained in the NEC. For example, if Type UF Cable is employed, the cable should be secured in place at intervals not exceeding 4-1/2 ft. and within 12 in. from a junction box in accordance with the provisions contained in Sec. 339-3 (a)(4) and 336-5.

#### 4.4 Rack Mount

Rack-mounted modules are secured to a supporting structure which in turn is fastened to the roof. Typically, this method of support is employed on flat roofs and sloped roofs which do not provide the proper angle for the array to achieve the most effective exposure to available sunlight.

Since it is likely that the module interconnect wiring will be subjected to weather, cable wiring systems including separable connectors, if employed, should be sunlight resistant and suitable for wet locations. Raceways should be made watertight and conductors contained within them should be suitable for wet locations. Junction boxes should be weatherproof.

The area containing the wiring system may be open and readily accessible, particularly on an easily accessible roof. Accordingly, if the wiring system for module interconnection consists of cable, the installation should provide for protection of the cable against physical damage as specified in the appropriate NEC article covering the wiring system used.

Consideration should be given to the support of wiring systems, especially if the installation is located in a geographical area where ice and snow accumulation can occur. For such areas, securement by straps or the equivalent at intervals smaller than required by the NEC may need to be provided.

#### 4.5 Ease of Installation, Inspection and Maintenance

Ease of installation, inspection and maintenance is an important aspect of the requirements for photovoltaic wiring systems. To facilitate wiring installation, it is desirable to employ a method of wiring termination which provides a simple means for connection and disconnection and which necessitates the use of only a minimum number of tools. This will also minimize the possibility of making connection errors and enhance serviceability of the system.

A wiring system employing a method of termination of intermodule wiring that requires cutting of conductors to accomplish module replacement should be avoided. Wiring terminations should be made by: 1) the use of separable connectors; 2) by making fixed wiring connections to terminals; or 3) splices to integral module leads.

The use of separable connectors provides a means for connection and disconnection of individual modules which greatly enhances the ease of installation of modules and disassembly of the array. Separable multipole connectors designed for photovoltaic use are required to be polarized to reduce the possibility of misconnection. Single pole separable connectors designed for photovoltaic use are required to be configured or arranged so that the mating connector for one will not be accepted by another and vice-versa, if such is an improper connection. Live parts within PV connectors are required to be recessed or guarded to protect against accidental contact by persons, and this simplifies servicing of the system. Some PV connectors are designed for field attachment to intermodule wiring by the use of a special tool. Such tools should be available from the connector manufacturer.

Terminals, if employed, should consist of either pressure terminal connectors or wire binding screws. It is suggested that solder type terminals not be employed because this type of connection is not easily accomplished in the field. Also, soldered connections do not provide an easy method of disconnection of panels for repair of the system. Additionally, in the event the soldered splice or termination is subjected to excessive moisture, undue corrosion of the connection can be expected.

To minimize the possibility of connection errors and to assist in trouble shooting the system, the conductors should be identified by color coding. The polarity of wiring terminals, leads and separable connectors should be clearly marked. Identification of the grounded conductor of the system is required by the NEC.

To enhance serviceability of fixed wired systems having integral module leads, it is suggested that splice connections be made by wire connectors which can be readily removed. This can be accomplished by the use of pressure cable connectors, such as twist-on-wire connectors, sometimes called "wire nuts", which do not require the use of a special tool for assembly. Welded and soldered splice connections should be avoided.

Weatherproofing of connections in fixed wiring systems should be accomplished by containing the connections inside weatherproof junction boxes. Constructions involving application of potting materials or conformal coatings after field connections are made should be avoided, because this construction can prevent inspection and reduce serviceability of the system.

To facilitate maintenance of the system, junction pull and outlet boxes and separable connectors should be located where internal wiring can be rendered accessible. For integral- and rack-mounted panels, accessibility to connections can be readily achieved because the back side of the modules is usually in a relatively open area. Junction, pull, and outlet boxes and separable connectors, located behind direct- and standoff-mounted modules, should be installed so that access to the connections can be accomplished by displacement of a module(s) or panel(s) secured by removable fasteners and connected by a flexible wiring system.

#### 4.6 Disablement

To reduce the risk of electric shock to persons during servicing of the PV system, it is necessary to provide a means to disable the array or portions of the array as required by the NEC, Section 690-18.

A means to disable an array or parts of an array can be incorporated into the wiring system. The module connections and the wiring system can be arranged such that (a) individual modules can be rendered nonhazardous by disengagement of separable connectors, and (b) parts of the wiring system can be disconnected from other parts of the array which are still connected in a hazardous energy circuit by disengagement of separable connectors of two or more modules. The connectors are required to be constructed and installed so as to guard against inadvertent contact with live parts by persons. In general, this necessitates that the connectors have recessed contacts. Requirements for the connectors are indicated in App. A to this Report.

In some installations switches are incorporated in the PV system to segment the array circuits into nonhazardous portions. This method may involve considerable amount of additional wiring unless it is feasible to install the switches adjacent to (and underneath) the modules, such as in a rack-mounted array.

Another method that can be used to accomplish disablement is to shield the array from illumination thus depriving it of capacity to develop hazardous energy. Depending on the type of connections in the array, all of the array or portions of the array may need to be covered with an opaque material to render system components serviceable. Although this method would not be permanently incorporated as part of the system, and is often difficult to achieve in actual practice, it can be used effectively to service the wiring system.

## 5. NEC WIRING SYSTEMS

Sec. 690-31 of the NEC permits all raceway and cable wiring methods included in the Code to be used on PV arrays. The following paragraphs contain definitions of each of the wiring systems. Also, based on the provisions of the NEC, the applicable permitted uses and use-restrictions as involved in PV applications are indicated. For each wiring system, commentary is provided indicating the advantages and disadvantages that are pertinent to PV applications.

The cable and conduit wiring methods described below include sixteen different systems. (Medium Voltage Cable, Type MV, Art. 326, is not considered applicable to PV systems because it is designed for voltages of 2001 to 35,000, which is out of the range of voltages for systems anticipated by Article 690). The presentation of the articles described below is not given in ascending numerical order, nor is the order based on the relative merits of the various wiring systems. The discussion on cable wiring systems begins with Article 336-Nonmetallic-Sheathed Cable because some of the provisions contained in this article are referenced in other articles covering cable wiring methods. Likewise, the discussion on conduit wiring system begins with Article 346-Rigid Metal Conduit because some of the provisions contained in this article are referenced in other articles covering other types of conduit wiring systems.

In addition, the NEC contains Articles on open wiring on insulators (Art. 320), messenger supported wiring (Art. 321), and concealed knob and tube wiring (Art. 324). These methods are also discussed. Flexible cord and flexible cables (Art. 400) are covered separately in Sec. 8.2 of this document.

Unless otherwise stated, the article, section, chapter, and table references herein, pertain to the National Electrical Code, 1984 edition.

Some of the wiring systems include lead-covered conductors. Although there may be a question on the availability of such conductors, they have been included in the following material for completeness.

5.1 Article 336-Nonmetallic - Sheathed Cable  
(Types NM & NMC)

Nonmetallic-sheathed cable, commonly and generally known as "Romex", is a factory assembly of two or more insulated conductors having an outer sheath of nonmetallic material. Type NM cable has an overall covering of fibrous or plastic material which is flame retardant and moisture resistant. Type NMC cable is similar, but the overall covering is also fungus resistant and corrosion resistant. The letter "C" indicates that it is corrosion resistant. Type NM cable is restricted to use in dry locations and Type NMC cable can be used in dry, moist and damp locations.

Types NM and NMC cable are available with sizes No. 14 through No. 2 AWG copper conductors and with sizes No. 12 through No. 2 AWG aluminum or copper-clad aluminum conductors. The conductors are rated 75 or 90°C depending on the type of conductor insulation. The cables have jackets rated 60°C and may have conductors rated 60, 75 or 90°C depending on the type of conductor insulation provided. The ampacities, regardless of the conductor temperature rating are those of 60°C conductors specified in Table 310-16.

The permitted uses for and advantages of nonmetallic-sheathed cable are: (1) it is one of the most widely-used cables for branch circuits and feeders in residential and light commercial wiring systems, therefore, widely available; (2) easy to install; (3) comparatively inexpensive; (4) may be used as either exposed or concealed wiring; (5) can be fished in concealed portions of finished buildings; and (6) use with separable connectors for wiring terminations is feasible.

The use-restrictions and disadvantages for nonmetallic-sheathed cable include: (1) the cable is not suitable for wet locations nor is it sunlight resistant; (2) requires protection from physical damage when located in accessible areas and/or when the cable passes through studs, joists, rafters and similar members; (3) not permitted in dwellings or structures exceeding three floors above grade; and (4) Type NMC cable is not readily available because Type UF cable is usually used in its place.

For arrays containing integral-, standoff-, or rack-mounted modules, cable support should be provided in accordance with the provisions contained in Sec. 336-5. These provisions specify that the cable is to be secured by staples, straps or similar fittings at intervals not exceeding 4-1/2 ft and within 12 in. from each box. For old work or retrofit installations where the cable is fished in concealed locations, this requirement is waived. The roof or deck may be considered to provide support of cables of minimum length needed for interconnections between standoff-mounted modules. Roofs having a rise equal to or less than 4 in. per horizontal foot may provide the necessary support. On steeper roofs such support may be questionable.

Bends in the cable should be gradual so as not to injure the protective covering of the cable. The provision contained in Sec. 336-10 states in essence that if the bend was continuous so as to form a complete circle, the diameter of the circle should be at least ten times the diameter of the cable. The primary application of this provision is likely to be encountered in the installation of standoff-mounted modules where the clearance space between the modules and roof may be only a few inches and where the cable exits the module or junction box normal to the roof surface.

Where nonmetallic-sheathed cable is run exposed in accessible attics or roof spaces, protection against mechanical damage is required by Secs. 336-9 and 333-12. These provisions are particularly applicable to arrays containing integral-mounted modules. Essentially, these provisions require that where the cable is run across the top of floor joists or across the face of rafters or studs within 7 ft. of the floor joists, protection may be provided by: (1) running the cable along the sides of the joists and rafters; or (2) the use of a guard strip on each side of the cable where the cable is routed across the face of rafters or joists. Where cable is routed through bored holes in joists, rafters or similar structural members, protection can be provided by either locating the hole in the center of the member or by the use of notches and steel plates in accordance with Sec. 300-4.

For arrays containing rack-mounted modules, protection against physical damage is also needed for cable runs exterior to the building. This can be provided by: (1) enclosing the cable in conduit; (2) routing the cable close to the back side of the module; (3) routing the cable to follow the surface of the building or array structural members; or (4) securing the cable to running boards.

## 5.2 Article 338 - Service-Entrance Cable, Types SE and USE

Service-entrance cables are single-conductor or multi-conductor assemblies with or without an overall covering. They are primarily used for providing electrical service to buildings and are of the following types: (1) Type SE has a flame-retardant, moisture-resistant covering for above ground installation; and (2) Type USE is identified for underground use and has a moisture-resistant covering which does not have to be flame retardant. Both Types SE and USE are not required to incorporate the equivalent of a metal shield for inherent protection against mechanical abuse.

Unarmored service-entrance cable, Type SE, is similar in construction to Type NM cable. The significant difference between these cables is that Type NM cable contains thermoplasticinsulated conductors whereas Type SE cable contains thermoset- (rubber) insulated conductors. Also, another significant difference is that Type SE cable may have the neutral conductor uninsulated. Sec. 338-4 permits Type SE cable, but not Type USE, to be used for interior branch-circuit conductors. Part (b) of Section 338-4 specifies that the installation of unarmored Type SE cable be made in accordance with the provisions contained in Article 336 (Type NM cable). Accordingly, the considerations regarding cable support, protection against physical damage and cable bends described above for Type NM cable are also applicable to unarmored service-entrance cable. Although the cost of Type SE cable may be higher than that of Type NM cable, it is readily available and is often used in applications where part of the circuit is located outdoors.

Service-entrance cable is available with sizes No. 12 AWG and larger copper conductors and No. 10 AWG and larger aluminum or copper-clad aluminum conductors. The temperature rating is 75 or 90°C depending on the conductor style provided. A maximum temperature rating of 75°C applies for wet locations. The cable can be used in dry and wet locations and is sunlight resistant.

In addition to having all the advantages indicated above for nonmetallic-sheathed cable, service-entrance cable is suitable for use in wet locations. Accordingly, it may be considered for use with integral-, direct-, standoff- and rack-mounted modules. Service-entrance cable having a smooth and round circumference is available. Fittings and connectors that provide a watertight securement and connection means for this type of cable, designated Style SER, are available.

One consideration involved with service-entrance cable is that protection against physical damage is to be provided when this cable is run exposed in accessible attics or roof spaces. The methods of providing protection against physical damage for Type NM cable are applicable to service-entrance cable. Another disadvantage is that service-entrance cable is not available in conductor sizes smaller than No. 12 AWG. This is a drawback only for applications where, based on the output current rating of individual modules, smaller conductor sizes would suffice for module interconnect wiring.

### 5.3 Article 339 - Underground Feeder and Branch-Circuit Cable (Type UF)

Underground feeder and branch-circuit cable is provided with single or multiple conductors in sizes ranging from No. 14 AWG copper or No. 12 AWG aluminum or copper-clad aluminum through No. 4/0 AWG. The conductors have moisture-resistant insulation. The ampacity of Type UF Cable is that of 60°C conductors specified in Table 310-16. In addition to the insulated conductors, the cable is permitted to have an approved size of insulated or bare conductor for equipment grounding purposes only. The overall covering is flame-retardant, moisture-, fungus- and corrosion-resistant and suitable for direct burial in the earth.

In addition to having all of the advantages indicated above for nonmetallic-sheathed cable, underground feeder cable is suitable for use: (1) in wet locations; and (2) outdoors if marked "Sunlight Resistant." Although underground feeder cable maybe slightly more expensive than nonmetallic-sheathed cable, it is widely used and widely available.

Part (b) of Section 690-31 covering wiring methods for solar PV systems permits single-conductor underground feeder cable to be installed in the same manner as Type UF multiconductor cable in accordance with the provisions of Article 339 (Type UF cable). This provision permits a conductor to be routed separately from the other circuit conductors. This is an important provision that permits module series connections by single-conductor cables without having to run the other circuit conductor with it, as is normally required for AC circuits, thus reducing the amount of conductor material needed to wire an array.

Part A of Section 339 specifies that Type UF cable, when used as interior wiring, is to be installed as nonmetallic-sheathed cable in accordance with the provisions of Article 336. Accordingly, the considerations regarding cable support, protection against physical damage and cable bends described above for Type NM cable, are also applicable to Type UF cable.

#### 5.4 Article 340 Power And Control Tray Cable (Type TC)

Type TC cable is a factory assembly of two or more insulated conductors, with or without associated bare or covered grounding conductors under a nonmetallic sheath intended for installation in cable trays (Article 318), in raceways or where supported by a messenger wire. Type TC cable is available in conductor sizes of Nos. 18 AWG through 2000 MCM copper and size Nos. 12 AWG through 2000 MCM aluminum or copper-clad aluminum. Type TC cable with conductors in size No. 14 AWG and larger copper and size No. 12 AWG and larger aluminum or copper-clad aluminum contains general wiring conductors which are suitable for branch circuit and feeder circuits. Size Nos. 18 and 16 AWG copper conductors of Type TC cable are fixture wires. The ampacity is in accordance with Section 400-5, except that Section 318-10 applies to conductors smaller than size No. 14 AWG. If the type designation of the conductors is marked on the outside surface of the cable, the temperature rating of the cable corresponds to the rating of the individual conductors. When this marking does not appear, the temperature rating of the cable is 60°C unless otherwise marked on the surface of the cable. The outer sheath is flame-retardant, nonmetallic material.

Type TC cable is used primarily in industrial applications where it is located in open or covered trays that are installed as a complete system. The permitted uses for and advantages of Type TC cable are: (1) easy to install; (2) use of separable connector for wiring terminations is feasible; (3) can be installed outdoors provided that the cable is identified as sunlight-resistant; (4) available in small conductor sizes of No. 18 and 16 AWG (copper); and (5) comparatively inexpensive and widely available.

The use-restrictions and disadvantages of Type TC cable include; (1) not permitted to be installed where exposed to physical damage; (2) not permitted to be installed as open cable on brackets or cleats.

5.5 Article 333 - Armored Cable  
(Type AC)

Type AC cable, commonly known as "BX", is a fabricated assembly of insulated conductors within a flexible spiral wrap of steel having interlocking edges. It is available in conductor sizes of Nos. 14 through 1 AWG copper and No. 12 through No. 1 AWG aluminum. The conductors are rated 60, 75 or 90°C depending on the conductor insulation. Ampacity of the conductors is in accordance with Table 310-16. Except for Type ACL, (which contains lead-covered conductors and which may not be available), an internal bonding strip of copper or aluminum in intimate contact with the armor is provided to supplement the effectiveness of the spiral armor as an equipment grounding means.

The provisions of Sec. 333-6 are such that Type AC armored cable can commonly be used in various types of power and light branch circuits and feeders. It can also be used for signal and control circuits. The flexibility of the cable and mechanical protection provided by the metal armor makes this system attractive for ready installation in new construction and rewiring jobs.

Type AC cable is required to be supported by the use of approved staples, straps, hangers or similar fittings at intervals not exceeding 4-1/2 ft. and within 12 in. from every outlet box or fitting. Exceptions to this includes: (1) areas where the cable is fished; and (2) lengths of not more than 2 ft. where flexibility is necessary.

The considerations for Type AC cable regarding cable bends, protection against mechanical damage in accessible attics, through studs, joist and rafters are the same as those indicated above for Type NM cable. Even though the cable has metal armor, a nail can penetrate the conductors of a cable passing through a structural member, such as a wall stud, unless the specified protection is provided.

The permitted uses for and advantages of Type AC cable include: (1) may be used as either exposed or concealed wiring; (2) can be fished in concealed portions of finished buildings; (3) is readily available; and (4) suitable for use outdoors provided that the cable employs lead-covered conductors (Type ACL). However, the latter item may be academic, because cable with lead covered conductors may not be available.

The use-restrictions and disadvantages of Type AC cable include: (1) not as easy to install as nonmetallic-sheathed cables because of the additional labor needed to cut the armor resulting in comparatively higher overall costs; (2) separable connectors for use with armored cable have to be specially designed; and (3) when located in accessible areas and/or when the cable passes through studs, joists, rafters, and similar members, protection against physical damage as indicated above for Type NM cable is required.

#### 5.6 Article 334-Metal-Clad Cable (Type MC)

Type MC cable is constructed in three designs: (1) interlocked metal type; (2) corrugated tube; and (3) smooth tube. All are intended for above-ground use, except when marked for direct burial. Type MC cables, which are suitable for direct burial, use in cable trays, or in direct sunlight are so marked.

For 600 V or less applications, insulated conductors in sizes No. 18 and 16 AWG as specified in Table 402-3 are available. The maximum temperature rating is 90°C and as permitted in Section 725-16. Conductors of larger sizes and of other temperature ratings as specified in Table 310-16 are also available.

For over 600 V applications, conductors in accordance with Tables 310-61 and 310-67 are available.

The interlocked metal Type MC cable is a heavy-duty industrial feeder type and is similar in appearance to Type AC cable. The smooth tube Type MC cable contains a continuous seamless aluminum tube as the outer sheath.

The provisions of Sec. 334-10 specify that Type MC cable is to be supported and secured at intervals not exceeding 6 ft. Interlocked metal Type MC cable is commonly supported on a cable tray permitted in part (b) of Section 334-10.

The provisions of Sec. 334-11 specify the minimum bending radii. Depending on the external diameter of the cable, the bending radius varies from 10 to 15 times the external diameter of the metallic sheath.

The permitted uses for and advantages of Type MC cable include: (1) may be used indoors or outdoors (wet locations require either a metallic covering impervious to moisture, a moisture impervious jacket (or a lead sheath) under the metal covering or use of insulated conductors suitable for wet locations); (2) may be used as exposed or concealed wiring; and (3) is readily available; and (4) can be obtained with a small conductor size of No. 18 AWG.

Some disadvantages of Type MC cable are: (1) not as easy to install as nonmetallic sheathed cables because of the additional labor required to cut and strip the armor, resulting in comparatively higher overall costs; and (2) separable connectors for use with Type MC cable have to be specially designed.

#### 5.7 Article 330 - Mineral-Insulated, Metal Sheathed Cable (Type MI)

A mineral-insulated metal-sheathed cable consists of one or more solid copper conductors insulated with highly compressed magnesium oxide and enclosed in a continuous copper sheath. It is available in sizes No. 16 AWG to 250 MCM one conductor, No. 16 to 4 AWG two- and three-conductor, No. 16 to 6 AWG four conductor and No. 16 to 10 AWG seven-conductor constructions. The conductors are rated 85°C and the ampacity is in accordance with Table 310-16. The outer copper sheath is liquidtight and gastight.

Because the construction of Type MI cable consists of inorganic materials, this cable provides a wiring material which is noncombustible, thus minimizing the risk of fire hazards resulting from faults or excessive overloads on electrical circuits. Type MI cable can be used indoors or outdoors and in wet or dry locations. It is commonly used in mines and other hazardous (classified) locations where flammable gases or vapors are present.

When Type MI cable is run through joists, studs, or rafters, protection against physical damage as described above for Type NM cable is required.

Type MI cable is required to be supported at intervals not exceeding 6 ft.

Disadvantages of Type MI cable include: (1) relatively expensive compared to the cost of other cables; (2) not easily installed; (3) not readily available; (4) end seals to keep moisture from entering the magnesium oxide insulation are required; and (5) special fittings are necessary for transition to other wiring systems.

#### 5.8 Article 337 - Shielded Nonmetallic-Sheathed Cable (Type SNM)

A shielded nonmetallic-sheathed cable is a factory assembly of two or more insulated conductors in an extruded core of moisture-resistant, flame-resistant, nonmetallic material, covered with an overlapping spiral metal tape and wire shield and jacketed with an extruded, nonmetallic material that is resistant to water, flame, oil, corrosion, fungus, and sunlight. The cable is available in Sizes Nos. 18 through 2 AWG copper and Nos. 12 through 2 AWG aluminum or copper-clad aluminum conductors.

Type SNM cable is provided with conductor sizes ranging from No. 18 AWG through No. 2 AWG copper and No. 12 AWG through No. 2 AWG aluminum or copper-clad aluminum. The ampacity and temperature rating of the conductors are in accordance with Tables 310-16, 402-3 and 402-5.

In accordance with Article 337-3, from a physical standpoint, Type SNM cable is limited to installation in cable trays or in raceways. The construction of the cable is such that it is permitted in hazardous (classified) locations under certain conditions.

The disadvantages of Type SNM cable include: (1) relatively high cost; (2) limited availability; (3) the limitation to cable trays or raceways; and (4) extra effort needed for connections and terminations.

#### 5.9 Article 363 - Flat Cable Assemblies (Type FC)

Type FC cable is a specialized wiring material intended for installation in a U-channel surface metal raceway which is specifically designed to contain the cable and to accommodate movable taps. The raceway is open along one side to allow positioning the taps at any location along the length of the raceway. The cable is an assembly of two, three or four parallel No. 10 AWG special stranded copper wires formed integrally with an insulating web. The temperature rating and ampacity of the conductors are in accordance with Tables 310-13, 310-16 and 310-18. The movable taps that are used in this system are provided with a conduit nipple for connection to conventional junction boxes and fixture boxes. The tap devices have "pin-type" contacts which make connection to the cable by piercing the cable insulation when fastened in place. Flat cable wiring systems are intended for indoor use only.

An attractive attribute of flat cable assemblies is that movable taps are used for making connections to loads which may be relocated from time to time. Since the location of PV modules is not likely to be changed after the initial installation, the movable connection feature loses its pertinence in PV applications. However, the ease of making the tap connections may be an advantage in some cases.

Because flat cable assemblies are available with only No. 10 AWG conductors, they are limited for use only on 30 A branch circuits. Also, an installation requires special hardware consisting of U-channel surface metal raceway and position taps. Accordingly, flat cable assemblies are seldom used and are not widely available. The overall costs for a flat cable wiring system is comparatively higher than other cable wiring systems. These features make its use relatively impractical for PV applications.

#### 5.10 Article 328 - Flat Conductor Cable (Type FCC)

Type FCC wiring system is intended for branch-circuit wiring to supply floor outlets in office areas and in other commercial and institutional interiors. The flat conductor cable is to be installed under carpet squares where it is sandwiched between a nonmetallic, adhesive-coated "rear shield" and a grounded metal "top shield". The adhesive on the back of the rear shield secures it to the floor while the adhesive on the top surface of the rear shield serves to hold the cable in place and completes the raceway by bonding the two shields together. Specially designed boxes, fittings and surface metal raceways complete the enclosure of the cable connections and permit connections to other types of wiring systems.

The use of Type FCC wiring system eliminates the need to penetrate the fixed interior finish of a building to install a new or relocate an existing power outlet. There is no need to drill concrete floors on fish flexible wiring systems into stud supported walls; only the carpet squares need to be raised for installation. Because installation of this wiring system involves special fittings, the system may not be as commonly available as other cable wiring systems, such as Types NM, UF or SE.

Some characteristics of a flat conductor cable wiring system that are useful for PV applications include: (1) the thin cross section of the cable (approximately 1/32 in.); and (2) can be mounted directly over building walls and floors. These characteristics make flat conductor cable particularly attractive for use in arrays having direct-mounted modules because for some direct-mounted modules, the back side of the modules are either in intimate contact with the roof or there is very little clearance space between the roof and the modules. This feature makes it difficult to utilize other types of wiring systems. The use of flat conductor cable wiring system would expedite the installation of the system and reduce overall costs.

The disadvantages of a flat conductor cable wiring system include: (1) not permitted to be used outdoors or in wet locations, nor in residential, school or hospital buildings; and (2) restricted to installations on smooth continuous surfaces which may not be provided by some roof deck constructions. With respect to Item (1), since the location of the wiring system in an array having direct-mounted modules is generally considered as damp, the use of flat conductor wiring systems would not be considered acceptable.

#### 5.11 Article 346 - Rigid Metal Conduit

In this method of wiring, all wires are enclosed in a steel or aluminum raceway called conduit which is used in conjunction with couplings, fittings and connectors. Steel conduit protected from corrosion solely by enamel is permitted for use only indoors and in occupancies not subject to severe corrosive influences. Accordingly, enamelled steel conduit is limited for use in arrays employing modules having watertight exposed surfaces, which together with the building construction provide an environment similar to indoors. Steel conduit having a galvanized finish and aluminum conduit can be used in arrays not having a watertight exposed surface because these conduits are suitable for outdoor use.

During installation all ends of conduit are required to be reamed to remove sharp edges. Connection of conduit to knockouts in sheet metal enclosure requires a bushing to protect the wires from abrasion and two locknuts (one inside and one outside).

The radius of bends and conduit should not be less than that specified in Table 346-10 so that the internal diameter of the conduit will not be effectively reduced. Also, to facilitate pulling of the conductors in the conduit, the number of bends in one run of conduit should not be more than four quarter-bends (360° total).

Conduit should be supported within 3 ft of each box, fitting, or cabinet and at intervals of not over 10 ft. However, if the conduit is in straight runs with threaded type couplings, the distance between supports for 1 in. trade size and larger conduit can be increased to that specified in Table 346-12.

The number of conductors permitted in a single conduit should not exceed the percentage fill specified in Chapter 9.

In outdoor applications, the conductor within rigid conduit may be subjected to moisture. Accordingly, wet-rated conductors (letter "W" in the type designation) should be utilized for arrays having rack-mounted, standoff-mounted, or direct-mounted modules. The primary advantages of rigid conduit are: (1) can be used in locations subject to severe physical damage; (2) conductors can be easily replaced or added; and (3) can be used outdoors.

Sec. 346-1(b) states that, where practical, dissimilar metals in contact anywhere in the system shall be avoided to eliminate the possibility of galvanic action. Accordingly, steel conduit should be routed so as not to come in contact with aluminum-module or panel frames. However, the Exception to Sec. 346-1(b) permits aluminum fittings and enclosures to be used with steel conduit. It has been established that aluminum fittings tested for the purpose and aluminum enclosures do not present a corrosion problem when used with steel conduit.

The disadvantages of rigid conduit include (1) not easily installed; (2) higher overall costs resulting from a relatively large amount of labor required for installation; and (3) nonflexibility of the conduit impedes serviceability of the system.

#### 5.12 Article 345 - Intermediate Metal Conduit

Intermediate metal conduit (IMC) is similar to rigid metal conduit but has lesser wall thickness. IMC uses the same threading method and standard fittings as rigid metal conduit. The general application rules that apply to rigid metal conduit also apply to IMC. IMC is acceptable under the NEC for all applications for which the heavier wall rigid metal conduit is permitted.

The same advantages and disadvantages outlined above for rigid metal conduit apply to IMC. Additionally, the thinner wall makes IMC lighter and less expensive than rigid metal conduit. The lighter weight of IMC also facilitates handling and installation.

### 5.13 Article 348 - Electric Metallic Tubing

Electrical metallic tubing (EMT) is similar to rigid metal conduit and intermediate metal conduit except that it is constructed with a thinner wall. EMT is permitted for both exposed and concealed work. Because EMT is lighter than conduit and is less rugged in construction, it is not permitted to be used in locations subjected to severe physical damage or to corrosive agents.

Because of the thin wall construction, EMT is not permitted to be threaded. Joints and connections are made with threadless fittings that hold by means of pressure. For outdoor applications, raintight fittings are available. These would be needed in arrays employing rack-mounted modules or standoff mounted modules having an exposed surface which is not watertight. The ends of EMT should be reamed or otherwise treated to remove sharp edges.

The rules concerning: (1) how bends are made; (2) the maximum number of bends permitted; (3) support; (4) maximum number of conductors permitted; and (5) avoiding contact between dissimilar metals to eliminate galvanic action are the same as that indicated above for rigid metal conduit.

The same advantages and disadvantages outlined above for rigid metal conduit apply to EMT. Additionally, its thinner wall construction and the use of threadless fittings makes EMT lighter and more economical to use than either rigid metal conduit or IMT.

### 5.14 Article 350 - Flexible Metal Conduit

Flexible metal conduit, commonly known as "Greenfield" or simply "Flex", is similar in appearance to armored cable but it is an empty raceway through which wires must be pulled after it is installed as a complete system. For outdoor applications (arrays employing rack-mounted modules, standoff-mounted, or direct-mounted modules), conductors suitable for wet locations ("W" - designated conductor types) should be utilized in order to comply with the provision contained in Sec. 350-2. However, the use of this conduit should be avoided in installations where water can enter into the flex and run into the terminal box. This concern is applicable to rack-mounted arrays.

In accordance with Sec. 350-4, flexible conduit should be supported within 12 in. of every box, cabinet or fitting and also at intervals not exceeding 4-1/2 ft. This provision is waived for: (1) areas where the conduit is fished; (2) lengths not over 3 ft at connections to equipment where flexibility is necessary; and (3) 6 ft length between a recessed lighting fixture and a junction box.

A separate grounding conductor must be used with flexible metal conduit. Per Sec. 350-5, this provision is waived when: (1) both the conduit and the fittings are approved for grounding; (2) the total length in any ground return path is 6 ft or less; and (3) the circuit conductors are protected by overcurrent devices rated 20 A or less.

To minimize the possibility of damaging the conductor insulation, Sec. 350-6 specifies that a run of conduit should not contain more than four quarter bends.

The use of flexible metal conduit provides flexibility at connections which is an advantage over rigid metal conduit, EMT and IMC, thus enhancing serviceability of the system. Flexible metal conduit is comparatively inexpensive and is readily available to contractors who generally purchase in quantities consisting of full reels or full cartons. Some disadvantages are the restrictions indicated above concerning outdoor use and grounding.

#### 5.15 Article 351 - Liquidtight Flexible Conduit

Part A of Article 351 covers liquidtight flexible metal conduit which is similar in construction to ordinary flexible metal conduit except that an outer liquidtight nonmetallic sunlight-resistant jacket is provided. It is commonly called "Sealtite".

Liquidtight flexible metal conduit is permitted to be used in both exposed and concealed work where conditions of installation, operation or maintenance require flexibility or protection from liquids or vapors. It is not permitted to be used where subject to physical damage.

The rules for supporting and maximum number of bends are the same as those indicated above for flexible metal conduit.

A separate equipment grounding conductor should be installed, although under limited conditions stated in Exception No. 1 to Section 351-9, the conduit may be used for grounding purposes.

Part B of Article 351 covers liquidtight flexible nonmetallic conduit which may be used only for industrial applications. It is not permitted to be used in any individual length exceeding 6 ft and is limited to a maximum of 1-1/2 in. trade size. A separate conductor is required to be installed for equipment grounding. The primary application of this conduit is in the machine-tool industry.

In addition to having the advantages indicated above for flexible metal conduit, liquidtight flexible conduit can be used outdoors without any restrictions. Liquidtight flexible conduit is somewhat more expensive than flexible metal conduit. It is readily available to contractors who generally purchase in quantities consisting of full reels or full cartons. The need for a separate equipment grounding conductor is considered as a disadvantage for this wiring system.

#### 5.16 Article 347 - Rigid Nonmetallic Conduit

This article applies to a type of conduit and fittings of nonmetallic material that is resistant to moisture and chemical atmospheres. Although there are a number of materials used in the construction of nonmetallic conduit, only polyvinyl chloride (PVC) is suitable for use above ground.

PVC conduit is designed for connection to couplings, fittings and boxes by the use of a solvent type cement. All cut ends are required to be trimmed to remove sharp edges before connections are made.

In accordance with Sec. 347-8, rigid nonmetallic conduit is required to be supported at intervals specified in Table 347-8 and within 3 ft of each box, cabinet or other conduit termination. The excellent moisture and corrosive resistance, light weight and ease of installation have led to widespread use of PVC conduit. It is commonly used in industrial applications involving corrosive agents and vapors or mists of caustic, pickling acids, plating baths, and hydrofluoric and chromic acids. Except for some hazardous locations and for support of fixtures, PVC can generally be used wherever rigid metal conduit is permitted.

The use of PVC conduit requires some consideration of the maximum ambient temperature and the temperature rating of the conductors contained within the conduit. In accordance with Sec. 347-3, nonmetallic conduit is not permitted to be used with conductors having a higher temperature rating than that of the conduit. The concern is that the conductors operating at temperatures higher than the rating of the conduit may result in degradation of the conduit.

PVC conduit is widely available and relatively inexpensive. Its use with couplings, fittings and boxes which are secured by solvent cement reduces the labor required for installation resulting in substantially reduced overall-costs.

Some drawbacks in the use of rigid nonmetallic conduit are: (1) nonflexibility of the conduit impedes serviceability, (2) separate conductor needs to be installed for equipment grounding, and (3) its use within buildings reportedly may be restricted by some inspection authorities because of perceived fire hazards.

#### 5.17 Article 320 - Open Wiring On Insulators

Open wiring on insulators is an exposed wiring method using cleats, knobs and flexible tubing for protection and support of single insulated conductors run in or on buildings and not concealed by the building structure. Conductors for open wiring may be of any of the general-use types specified in Article 310. The temperature rating and ampacity are in accordance with Tables 310-17 and 310-19.

The materials used for open wiring on insulators are readily available and relatively inexpensive. This method of wiring is commonly used for high-tension work in transformer vaults and substations. It is also commonly used for temporary work and for runs of heavy conductors for feeders and power circuits as in manholes and trenches under or adjacent to switchboards to facilitate the routing of a large number of circuits into conduit.

In accordance with Sec. 320-3, open wiring on insulators is permitted only for industrial or agricultural establishments indoors or outdoors, in wet or dry locations where subject to corrosive vapors, and for services.

Sec. 320-6 contains the rules for conductor support. Noncombustible, nonabsorbent insulating materials are required to be used for supporting the conductors and the conductors are not permitted to contact any other objects. Supports are required: (1) within 6 in. from a tap or splice; (2) within 12 in. of a dead-end connection to a rosette, lampholder or receptacle; and (3) at intervals not exceeding 4-1/2 ft. Some exceptions to the above are specified in this section.

Open conductors passing through walls, floors and wood cross-members are required to be separated from contact with walls, floors, wood cross-members or partitions through which they pass by tubes or bushings of noncombustible, nonabsorbent insulating material.

In accordance with Sec. 320-12, open conductors should be spaced at least 2 in. away from metal piping, metal objects, and exposed conductors of other circuits. Alternatively, a continuous and firmly fixed nonconductive material, in addition to the insulation on the conductor, may be used to separate the conductors from metal piping, metal objects and other exposed conductors.

Special considerations regarding protection of conductors against physical damage must be given to open wiring on insulators. The provisions covering this area are contained in Secs. 320-14 and -15. They apply to conductors within 7 ft from the floor, in unfinished attics and roof spaces. These considerations are applicable to arrays employing integral-mounted modules and to arrays employing rack-mounted modules which are accessible. See preceding Section 4 entitled "Requirements For Photovoltaic Wiring Systems" for further details.

There are a number of disadvantages in the use of open wiring on insulators which makes this wiring method unattractive for PV use. These disadvantages are: (1) restricted for use only in industrial and agricultural establishments; and (2) the special precautions that must be taken during installation are not easily accomplished. These special precautions are: (1) 2 in. minimum clearance requirement between conductors and metal objects; (2) the conductor support requirement which includes the restriction against conductor contacting objects; and (3) for some applications, elaborate measures must be taken to provide protection of the conductors against physical damage.

#### 5.18 Article 324 - Concealed Knob-And-Tube-Wiring

Concealed knob-and-tube-wiring is a wiring method consisting of knobs, tubes and flexible nonmetallic tubing for the protection and support of single insulated conductors concealed in hollow spaces of walls and ceilings of buildings. Conductors may be of any of the general-purpose types specified in Article 310.

Where the conductors are run on knobs or through tubes in a closed-in and inaccessible attic or roof space, the wiring is considered as concealed knob-and-tube work. If the wires are contained in an attic roof space which is accessible, the wiring must be protected from physical damage as indicated above for open wiring on insulators, Article 320.

Concealed knob and tube wiring is not considered as a general-purpose wiring method for new electrical work. It is restricted to use only for extensions of existing installations and elsewhere only by special permission granted by the local inspection authority having jurisdiction. This wiring method was used in the early days of electrical wiring and is very rarely used today. Accordingly, the knobs and tubes used in concealed knob and tube wiring may be scarce in some locations. Although the cost of the materials used in this wiring method is comparatively low, the labor needed to provide the required protection of conductors from physical damage will tend to cancel out this reduced-cost benefit.

The provision specified in Sec. 324-3 requiring that concealed knob and tube wiring be contained in unfinished attics and roof spaces narrows the use of this method for PV applications to arrays employing integrally-mounted PV modules. The additional restriction that this wiring method be used for extensions of existing installations, which would likely be found in older homes, further narrows the use of this wiring method, since integrally-mounted PV modules are not likely to be used in retrofit PV installations on existing homes.

#### 5.19 Article 321 - Messenger Supported Wiring

Messenger supported wiring is an exposed wiring support system using messenger wire to support insulated conductors by any one of the following: (1) a messenger with rings and saddles for conductor support; (2) a messenger with a field-installed lashing material for conductor support; (3) factory-assembled aerial cable; or (4) multiplex cables utilizing a bare conductor, factory-assembled and twisted with one or more insulated conductors such as duplex, triplex or quadruplex type of construction.

The following cable types are permitted to be installed as messenger supported wiring: (1) mineral-insulated, metal-sheath cable (Article 330); (2) metal-clad cable (Article 334); (3) multiconductor service-entrance cable (Article 338); (4) multiconductor underground feeder and branch-circuit cable (Article 339); (5) power and control tray cable (Article 350); and (6) other factory assembled, multiconductor conductor control, signal, or power cables which are identified for the use. Part (b) of Sec. 321-3 identifies some additional types of cables that are permitted only for industrial establishments.

Messenger supported wiring is widely used as: (1) service-drop cable for the utility supply to commercial and residential properties; and (2) overhead runs between buildings. The materials used in messenger supported wiring systems are readily available and comparatively inexpensive.

A practical PV application of messenger supported wiring may be for terrestrial arrays located away from the building. For such installations located in areas where burial of the conductors is not easily accomplished (such as rocky terrain), messenger supported wiring could be utilized for the PV output circuit conductors.

## 6. CANDIDATE WIRING SYSTEMS

An assessment of the permitted uses, use-restrictions, advantages and disadvantages of the wiring systems described above suggests that the following systems can be considered as candidate systems for use in PV arrays:

- 1) Nonmetallic-Sheathed Cable, Type NM.
- 2) Service-Entrance Cable Types SE and USE.
- 3) Underground Feeder and Branch-Circuit Cable, Type UF.
- 4) Power and Control Tray Cable, Type TC.
- 5) Flat Conductor Cable, Type FCC.

Each candidate wiring system has certain characteristics making it desirable for use in PV applications. However, for certain wiring systems, the NEC contains use-restrictions that may prohibit their acceptance in some PV applications by the local inspection authorities. One avenue for gaining broader acceptance by the inspection authorities would be to bring about appropriate revisions of the NEC. The following sections outline the considerations that need to be addressed in proposed revisions to the National Electrical Code for the purpose of qualifying these candidate wiring systems for uses other than those presently indicated. In addition, construction and performance specifications for cable that could be identified as photovoltaic cable, Type PV, are discussed.

In order to expand the permitted uses of a wiring system, the proposals would have to demonstrate that all makes of the wiring system equipment under consideration have the necessary properties. This may not be possible, especially if changes in materials or construction would be necessary to accommodate the proposed uses, because all manufacturers of that category of wiring system may not find it beneficial to make changes. In such a case it may be more feasible for manufacturers who wish to have their product qualified for the expanded uses to submit the product to investigation with respect to the added requirements. The products which meet the requirements could then be identified as also suitable for the expanded use.

### 6.1 Nonmetallic-Sheathed Cable, Types NM and NMC

The advantages indicated for nonmetallic-sheathed cable suggest that Types NM and NMC cables provide a desirable wiring method for PV arrays. Because Type NM cable is suitable for only dry locations, it is applicable only to arrays having integral-mounted modules. For arrays employing direct-mounted modules having a watertight exposed surface, Type NMC cable, which is suitable for moist and damp locations should be employed. Since Types NM and NMC cable are not suitable for wet locations, they should not be used in arrays: (1) having modules which do not have a water tight exposed surface; (2) employing standoff-mounted modules where the area between the roof and the perimeter of the modules is open allowing water run-off and wind driven rain or snow to contact the wiring; and (3) employing rack mounted modules.

Qualifying Types NM and NMC cables for use in arrays indicated in the preceding paragraph, that are considered to be wet locations, would necessitate that these cables contain wet-rated conductors. The insulation of wet-rated conductors is made from compounds that are resistant to water and consequently the conductors are capable of withstanding an insulation resistance test while immersed in water. For rack-mounted modules, the cable would additionally need to be sunlight resistant since the cable would likely not be completely shielded from direct exposure to the sun. This would require that the compounds used in the construction of the jacket be capable of withstanding exposures to sunlight and water. Compounds that are suitable for such exposures are capable of withstanding tests consisting of weatherometer conditioning (Standard for Light and Water Exposure Apparatus for Exposure of Nonmetallic Materials, ASTM G23-1969 (1975), Carbon Arc Type). The NEC does not permit the use of nonmetallic-sheathed cable outdoors or in wet locations. Accordingly, conductors suitable only for dry locations (type designation does not contain the letter "W") and jacket materials which are not sunlight resistant are generally employed in the construction of nonmetallic-sheathed cable.

Types NM and NMC cable having upgraded wire insulation and sheath materials for water and sunlight resistance may need additional identification to distinguish them from the cable construction which do not have these properties.

It should be pointed out that the foregoing discussion on upgrading the wire insulation and sheath material for water and sunlight resistance would appear to be an attempt to develop a new product when a similar product having the added characteristics plus some others already exists, namely Type UF cable. (See discussion in Sec. 6.3 of this document.)

## 6.2 Service-Entrance Cable, Types SE And USE

Even though conductor sizes smaller than No. 12 AWG are not available in Types SE and USE cables, this wiring system has all of the favorable attributes of Type NM cable which are attractive for PV applications. Additionally, there are no use-restrictions which would preclude its acceptance in PV applications by the inspection authorities. Type SE cable can be used within the building, whereas Type USE cable is restricted to outside the building, but may be buried.

## 6.3 Underground Feeder And Branch-Circuit Cable, Type UF

In addition to having all of the attributes mentioned above for Types SE and USE Cable, underground feeder cable is available in conductor sizes down to No. 14 AWG. This is a desirable feature for some applications where the current rating of individual modules does not necessitate No. 12 AWG (smallest size for Types SE and USE) for module interconnect wiring. Another common feature between service-entrance and underground feeder cables is that there are no use-restriction which would preclude its acceptance in PV application by the inspection authorities.

Sec. 690-31(b) permitting single conductor Type UF cable to be installed in PV systems in the same manner as Type UF multiconductor cable makes this wiring system particularly attractive for making series connections of modules where only a single conductor is needed.

It should be noted that generally for AC systems all circuit conductors are required to be routed together to minimize impedance and facilitate functioning of overcurrent devices under fault conditions. This is not the case in PV circuits which are DC.

## 6.4 Power And Control Tray Cable, Type TC

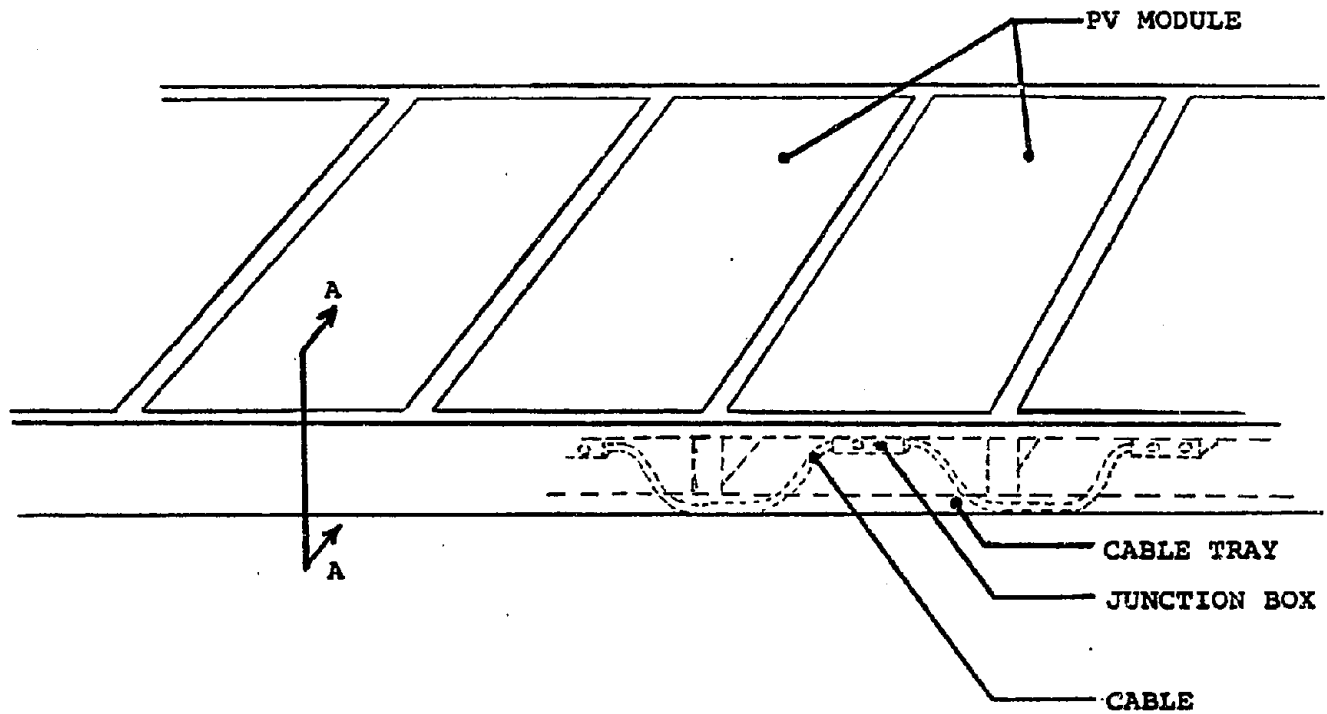
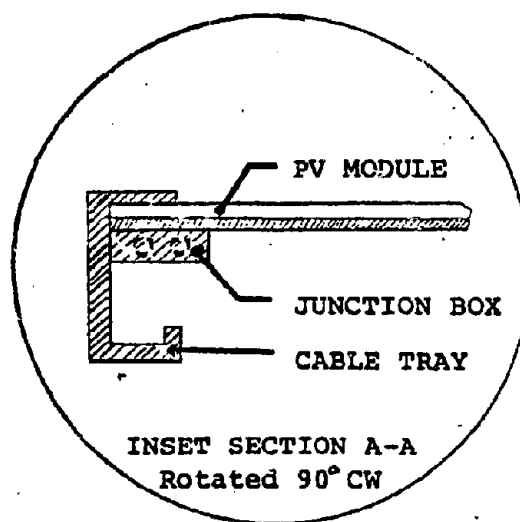
The weather-resistant properties of tray cable and the availability of this cable in conductor sizes of No. 18 and No. 16 AWG are attractive advantages for PV applications. If a suitable support method such as described in the following paragraphs is provided, tray cable could be considered for use in PV arrays employing rack-mounted modules and standoff-mounted modules, where the exposed surfaces and/or the area between the roof and module perimeter are not watertight.

Sec. 340-5 contains a use-restriction stating that tray cable shall not be installed as open cable on brackets or cleats. In order to gain acceptance of tray cable in PV applications by the inspection authorities, the installation should be made in accordance with Item 2 of Sec. 340-4 which states that tray cable shall be permitted to be used in cable trays or in raceways or where supported in outdoor locations by a messenger wire. Cable trays or raceways can be incorporated as part of the array. Raceways may consist of any of the conduit systems described in Sections 5.11 through 5.16 of this Report. A raceway may have to be used where the wiring penetrates a building wall. A cable tray could be incorporated into the design of the module frame by providing a side rail on the mounting flange. The construction could take the form shown in Fig. 6.4. If the junction box is located at the end of the module, the intermodule connecting cable could easily be placed in the tray to provide the required support for the cable.

An alternative to providing a raceway or cable tray would be to qualify tray cable for other methods of support. Support methods for Type NM Cable specified in Sec. 336-5 (staples, straps or similar fittings at intervals not exceeding 4-1/2 ft and within 12 in. from each box) would simplify the installation of this type of cable in PV arrays. In many applications the length of the intermodule connection cable is less than 12 in., in which case the fittings at each end would serve as the support for the cable.

Qualification of the tray cable for other methods of support could be accomplished by evaluating the tray cable in accordance with the specifications contained in Appendix B entitled "Outline of Proposal for Investigation of Solar Photovoltaic Cables". These specifications are similar to those required for UL Listed tray cable except that tests (for solar PV cable) include more mechanical abuse conditions than those required for UL Listed tray cable. Specifically, the additional tests include (following paragraph references pertain to the Appendix B): (1) Pulling Through-Joists Test (Par. 8.6.3); (2) Unwinding At Low Temperature (Par. 8.6.4); and (3) Abrasion Test (Par. 8.6.5) and Tension and Elongation Test (Par. 8.6.7). The methods of cable support specified in Appendix B are those contained in Article 336 (Type NM Cable) and Article 339 (Type UF Cable). A cable wiring material found to comply with the specifications contained in Appendix B by a qualified testing laboratory could then be identified also as Listed PV Cable.

FIG. 6.4



### 6.5 Flat Conductor Cable, Type FCC

Type FCC flat conductor cable has some features that make this wiring system attractive for use in PV arrays employing direct-mounted modules. However, the use of this wiring system in PV installations would most likely not be accepted by the inspection authorities because of the NEC restrictions which permit this wiring system for use only under carpet squares and not outdoors nor in wet locations.

Qualification of a flat conductor cable wiring system for PV use would necessitate an evaluation covering four areas of concern. For each of these areas, the evaluation should verify that: (1) electrical and mechanical properties of insulating materials are not adversely affected to the extent that a risk of fire or electric shock may result; (2) loss of circuit continuity that may cause arcing will not result; (3) live parts involving a risk of electric shock do not become accessible; and (4) that the wiring system complies with the dielectric voltage withstand requirements specified in UL 1703 after exposure to the conditions specified in the following paragraphs.

The first area of the evaluation would consist of conducting tests on the flat conductor cable to determine if the cable has the characteristics to withstand the environmental conditions prevailing in PV applications that are more severe than those encountered in the uses anticipated by Art. 328 of the NEC. Guidelines for conducting these tests are contained in the referenced UL Standard. For applications where the exposed surface of the direct-mounted array is watertight, the environmental conditions that need to be addressed are outlined below.

Wide Temperature Variations - PV modules experience extreme temperature variations. This is true particularly for installations in northern climates or higher elevations, where overnight ambient temperatures drop below freezing and the module surface temperature may reach as high as 90°C during the day under high irradiance levels. This will have an effect on the wiring system since it is in close proximity to the modules. The Temperature Cycling Test described in UL 1703 (Proposed First Edition of the Standard for Flat-Plate Photovoltaic Modules and Panels) would be applicable. This test specifies 200 temperature cycles between -40°C to +90°C.

Humidity - High humidity and freezing conditions may prevail for some installations. The Humidity-Freezing Cycle Test specified in UL 1703 (-40°C to 85°C at 85 percent RH) evaluates the effect of these conditions.

Insulating Materials - The selection of insulating materials used in flat conductor cable should take into consideration the temperature that will result on the back surface of the module during worst case operating conditions. In accordance with UL 1703, conditions of operation during the Temperature Test on PV modules include 100 mW/cm<sup>2</sup> irradiation in a 40°C ambient while operating in the following modes: (1) open circuit; and (2) reverse voltage, short circuit with one cell half-shaded. During each of these conditions of operation, the temperature of the wiring material should not exceed its temperature rating.

The second area of the investigation would include an evaluation of the connectors used for making connections to individual modules to verify that a reliable connection can be made. The following is a tabulation of the tests that would be conducted to evaluate this area. Guidelines for conducting these tests are contained in the referenced UL Standards.

1. Heat Cycling Test - UL 498, Standard for Wire Connectors
2. Static Heating Test - UL 498.
3. Contact Reliability Test - UL 498.
4. Impact Test - UL 1703.

The third area of the investigation would consist of conducting trial installations of the flat conductor cable and PV modules to determine that the system can be installed in a workmanlike manner without injury to the cable, the connectors and the modules. These trial installations would have to be conducted on a mock-up roof construction to simulate actual PV installation conditions. The ability of the wiring system to withstand the abuses inherent in a field installation would be evaluated during these trial installations.

The fourth area of the investigation would determine if there is a need for the top and bottom shields. The top shield, which is grounded metal, provides protection against electric shock in the event of an electrical fault. The adhesive coated back shield secures the wiring system in place. Depending upon the module design, it is possible that the concerns, which are alleviated by the use of these shields in installations anticipated by Article 328, may not be present in PV applications.

## 6.6 Photovoltaic Cable

A manufacturer may elect to produce a wiring system designed to have the essential attributes needed to meet the use conditions associated with PV applications. Such a wiring system could appropriately be designated as photovoltaic (PV) cable. Among the essential attributes of a PV cable wiring system to be considered are: (1) suitability for use in wet locations; (2) sunlight resistance; (3) ability to accommodate separable connectors for wiring terminations and connections; (4) ease of installation; (5) lower overall costs resulting from relatively low amount of labor required for installation; (6) usability either as exposed or concealed wiring; and (7) suitability for fishing in concealed portions of finished buildings.

The construction and test performance specifications outlined in Appendix B entitled "Outline Of Proposal For Investigation Of Solar Photovoltaic Cables" could be used as a guide in an investigation of a PV cable wiring system. These specifications are based on the essential attributes mentioned above that are needed for PV applications.

A cable wiring material found to have the necessary attributes for PV applications by a qualified testing laboratory could be identified as Listed PV cable. This would allow acceptance of this wiring system for use in PV installations by the inspection authorities.

## 7. WIRING TERMINATION METHODS APPLICABLE TO SOLAR PHOTOVOLTAIC ARRAYS

### 7.1 Introduction

There are various wiring termination methods permitted by the NEC for field applications. The purpose of this section is to identify and describe these wiring termination methods. Although each of these methods may be useable in PV arrays, certain methods have characteristics that enhance the ease of installation, inspection and maintenance of the PV systems. Sec. 4.5 of this document discusses in further detail the ease of installation, inspection and maintenance of PV wiring systems. Unless otherwise stated, reference to articles and sections contained in the following paragraphs pertain to the NEC.

The NEC requirements applicable to wiring termination methods are:

Terminals [Sec. 110-14 (a)] - Connection of conductors to terminal parts shall insure a thoroughly good connection without damaging the conductors and shall be made by means of pressure connectors (including set-screw type), solder lugs or splices to flexible leads.

Exception: Connection by means of wire binding screws or studs and nuts having upturned lugs or the equivalent shall be permitted for No. 10 AWG or smaller conductors.

Splices [Sec. 110-14(b)] - Conductors shall be spliced or joined with splicing devices suitable for the use or by brazing, welding, or soldering with a fusible metal or alloy. Soldered splices shall first be so spliced or so joined as to be mechanically and electrically secure without solder and then soldered. All splices and joints and the free ends of conductors shall be covered with an insulation equivalent to that of the conductors or with an insulating device suitable for the purpose.

The foregoing statements address termination methods that may be accomplished in the field, during PV equipment installation. The same methods may be utilized for factory-made internal connections, however, the factory-made connections are not limited to these methods. Internal connections of electrical equipment are subject to product Standard requirements. The topics below discuss the various types of field termination methods anticipated by Sections 110-14(a) and 110-14(b) and by Article 690.

Terminals and splices are required to be contained within an enclosure to: (1) protect against personal contact with hazardous live parts of the terminal and splice (uninsulated connections only); (2) protect the termination and its insulation from physical damage; and (3) to contain disturbances that may result from an electrical fault. If exposed to weather, enclosures including those provided as an integral part of a PV module (wiring compartments) are required to be weatherproof.

### 7.2 Terminations

Terminations at equipment can be made by: (1) connecting conductors to a fixed part, such as a terminal; (2) making splices to integral lead wires; or (3) mating PV system connectors, one of which is part of the equipment and the other is part of the wiring system. PV system connectors are discussed in Appendix A. Connections to terminals can be made as follows:

- By pressure terminal connectors which accomplish the connection of one or more conductors by means of mechanical pressure without the use of solder. Pressure terminals are of the set-screw or clamping plate type or the push-in terminal type.
- By wire binding terminals which include: (1) a wire binding screw and a terminal plate mounted to a base of insulating material; and (2) stud-and-nut type of terminal mounted to a base of insulating material. Proper connection of the conductor necessitates wrapping the conductor three-fourths of the way around the terminal screw before tightening. This method is limited to size No. 10 AWG and smaller conductors.
- By solder lugs which incorporate a means of mechanical securement of the connection before the application of solder.
- By splices to integral leads. This topic is discussed in the following section.

### 7.3 Splices

Generally, splice connections are made to connect a wiring system to integral leads of electrical equipment and to accomplish joining of circuit conductors, for example, at taps or at transition points of one type of wiring system to another.

A splice connection can be accomplished by means of: (1) the use of a crimp connector; (2) the use of a pressure cable connector; (3) insulation displacement connector; (4) brazing and welding; or (5) soldering. Splice connections are required to be provided with insulation equivalent to the conductor insulation or with an insulating device suitable for the purpose. The following paragraphs describe the foregoing types of splice connections:

- A crimp connector accomplishes the connection of two or more conductors by means of mechanical pressure without the use of solder. It requires the use of the proper tool for controlling the crimp. These connectors are in-line or cap-type and are either insulated or bare metal.
- Pressure cable connectors are designed to establish a connection between two or more conductors by means of mechanical pressure without the use of solder. This type of connector includes twist-on wire connectors, the barrel construction employing a set-screw(s) or two barrel-type connectors joined by a short bus. Variations of the foregoing may exist.
- Insulation displacement type of connection is accomplished by pushing an insulated, nonstripped wire between tapered tangs mounted within an insulating base. During assembly the tangs cut through the wire insulation and make contact with the conductor. A special tool may be needed for these connectors.
- Brazing and welding connections necessitate the use of a torch or the application of electrodes to the conductors and the energization of the electrodes. Generally, this method is employed under controlled conditions such as in a factory, not in the field.
- A soldered splice connection is required to be mechanically secured such as by twisting together before the solder is applied.

#### 7.4 Photovoltaic System Connectors

In accordance with Sec. 690-32, connectors are permitted to be used for on-site interconnection of PV modules and other PV array components providing that they are Listed for such use. Appendix A, entitled "Outline Of Proposal For Investigation Of Connectors For Use In Photovoltaic Wiring Systems," contains the construction and performance specifications that Underwriters Laboratories Inc. would apply to PV system connectors.

In developing the outline, UL utilized existing standards and established practices, and took into consideration the particular conditions encountered in the various types of PV arrays. The outline could be applied to presently existing connectors or it could be used in developing new designs.

To increase the level of PV system safety, it may be desirable to include bypass diodes in the wiring system. One convenient location for the diodes may be in the connectors portion not connected to a module. The outline does not include any concrete specifications in regard to such devices and it does not preclude them. However, inclusion of the auxiliary components may introduce additional considerations. For instance, a bypass diode may introduce higher temperatures which may necessitate use of polymeric materials with a higher temperature index. The need for heat sinking may introduce additional exposed dead-metal parts which may require bonding for grounding. The foregoing are only two examples of features which have to be considered with respect to the outline. It is to be noted that the relative advantages or disadvantages of incorporation of the auxiliary components in a working system are not the subject of this document.

## 8. MANUFACTURER'S INTERVIEWS

### 8.1 Introduction

Interviews with five manufacturers of PV modules were conducted for the purpose of: (1) identifying the various wiring systems and connection methods currently being used in PV installations; and (2) determining manufacturer's attitudes toward desirable attributes for wiring systems and connection methods used in PV installations. This information was considered along with the analysis of the use environment, in the development of appropriate proposed requirements for solar PV connectors and solar PV cable covered in Appendices A and B.

The information gathered during these interviews indicated that the wiring systems now used exhibit certain characteristics making them desirable for PV installations. These characteristics are enumerated in the following paragraphs.

For each wiring system currently being used by the manufacturers interviewed, it was found that noncompliance with certain provisions of the NEC existed. Consequently, it is likely that installations of these wiring systems may not be accepted by the local inspection authorities having jurisdiction in applying the NEC. These areas of noncompliance are detailed in the following paragraphs.

Because of the desirable attributes of some of the wiring systems used, it was felt that it would be beneficial to review the concerns that need to be addressed in the qualification of these wiring systems for PV use. These guidelines are outlined in the following paragraphs.

### 8.2 Flexible Cords and Cables

Flexible cord was found to be the most widely used of all wiring systems. The types of cords utilized ranged from junior hard usage cords, Types SJ and SJO to hard usage cords, Types SO and SEO. Type SEO Cord marked "W-A, Polar/Solar Cord" was also used. This cord was not listed by any electrical testing agency. The conductor sizes contained in the cords ranged from No. 20 AWG to No. 12 AWG.

The cord was terminated in junction boxes and secured to the boxes by the use of compression type cord-grip fittings. Securement of the cord to the module frame by the use of tie-wraps was found to be a common practice.

The desirable attributes expressed by manufacturers for a wiring system utilizing flexible cord included: (1) ease of installation; (2) flexibility which enhances handling of the module during installation and servicing; (3) availability of small conductor sizes of No. 18-16 AWG; (4) mechanical properties (particularly for Type SO) to provide resistance to abuse during installation and servicing of the module; (5) resistance of outdoor use cords to the effects of weather; (6) usability with presently available separable connectors for making wiring terminations; and (7) dimensions, i.e., the smooth and round circumference of the cord facilitating a watertight securement means through the use of compression type cord-grip fittings.

Commentary:

The marking "W-A" on a flexible cord signifies that it is suitable for outdoor use. The marking "Polar/Solar Cord" is apparently a proprietary marking. Information explaining its significance was not available.

As noted above, minimum conductor size of No. 20 AWG was contained in some cords. This is not in accordance with Article 400 which, except for tinsel cords and elevator cords, specifies a minimum conductor size of No. 18 AWG.

Sec. 400-7 which indicates the permitted uses of flexible cords and cables states that "flexible cords and cables shall be used only for: (1) pendants; (2) wiring of fixtures; (3) connection of portable lamps or appliances; (4) elevator cables; (5) wiring of cranes and hoists; (6) connection of stationary equipment to facilitate their frequent interchange; (7) prevention of the transmission of noise or vibration; (8) appliances where the fastening means and mechanical connections are designed to permit removal for maintenance and repair; or (9) data processing cables as permitted by Sec. 645-2. Since it is not anticipated that PV modules will be replaced frequently, Item 6 does not appear to be applicable. Moreover, the Proposed First Edition of the Standard For Flat-Plate Photovoltaic Modules and Panels, UL 1703, does not permit flexible cord as the connection means for PV modules. Commentary on the other items of Section 400-7 is not provided since it is clear that they do not apply to PV applications.

Sec. 400-8 indicates the uses which are not permitted for flexible cords: "unless specifically permitted in Sec. 400-7, flexible cords and cables shall not be used: (1) as a substitute for fixed wiring of a structure; (2) where run through holes in walls, ceiling or floors; (3) where run through doorways, windows, or similar openings; (4) where attached to building surfaces; or (5) where concealed behind building walls, ceiling, or floors. Flexible cord used in PV wiring systems would be considered as a substitute for fixed wiring of a structure. This would not be in compliance with Item 1. Also, it is likely that in some PV applications, the wiring may: (1) pass through holes in walls; (2) be attached to building surfaces; or (3) be concealed behind building walls. Such installations would clearly be in violation of provisions contained in Sec. 400-8.

In view of the use-restrictions for flexible cords enumerated above, PV installations containing wiring systems utilizing flexible cord may not be acceptable to the local inspection authorities.

However, if a cord is shown to be able to resist the effects encountered in PV installations, such a cord could then be identified also as PV cable.

Qualification of cords for use in PV applications would necessitate tests and an evaluation of the cord to determine that it has the characteristics necessary to withstand the environmental conditions prevailing in PV applications. Guidelines for such an evaluation are contained in Appendix B entitled "Outline Of Proposal For Investigation Of Solar Photovoltaic Cables".

Although Types S, SE, ST flexible cords are extra hard usage cords, which may withstand the mechanical abuse tests outlined in Appendix B, there are two areas of construction that are characteristic of flexible cord which may not comply with the test requirements specified in Appendix B. These two areas are flammability characteristics and moisture resistance properties of the conductors.

Because the requirements contained in the Standard For Flexible Cord and Fixture Wire, UL 62 do not include a Flammability Test, flexible cord is generally not constructed of compounds containing a flame retardant additive. Accordingly, it is likely that flexible cord would not comply with the flammability test requirements specified in Sec. 8.7 of Appendix B. All of the general purpose conductors and cable wiring materials specified in Chapter 3 of the NEC (with a few exceptions) are required to exhibit a flammability characteristic sufficient to reduce the risk caused by fire propagating along its length and the emission of flaming drops or particles.

Although outdoor use flexible cords (marked "W-A") employ jackets which are made from compounds that are sunlight resistant, the requirements contained in UL 62 do not require that the conductors themselves be wet-rated. As discussed in Sec. 4 of this document, which outlines the requirements for PV wiring systems, this construction of wiring would not be suitable for use in PV arrays employing: (1) rack-mounted modules; (2) standoff-mounted modules; or (3) direct-mounted modules. For these applications, wet-rated conductors should be utilized. General-purpose conductors and cable wiring materials specified in Chapter 3 of the NEC that are wet-rated (signified by the letter "W" in the type designation) are made from compounds that are resistant to water and consequently are capable of withstanding an insulation resistance test while the conductors are submersed in water. Since this is not a requirement in UL 62, it is likely that flexible cord would not comply with this test requirement. The requirements for insulation of conductors contained in PV cable are contained in Sec. 5.2 of Appendix B.

As indicated above, it was noted that on some presently manufactured modules, the flexible cord was secured to the module frame by means of tie-wraps. This method can provide a secure means of support without injuring the cord. Wire positioning devices which have been investigated for a declared purpose are available.

### 8.3 Power and Control Cable, Type TC

Type TC Cable marked "Sun Res., Direct Burial" was found to be used for some applications. The cable was supported by tie-wrapping to the module frame and terminated at junction boxes. Compression type cord-grip fittings were utilized for attachment of the cable to the junction boxes.

The desirable attributes of a wiring system utilizing Type TC Cable expressed by manufacturers included: (1) ease of installation; (2) availability of small conductor sizes of No. 18 AWG; (3) Suitability for outdoor use of cable marked "Sun Res."; (4) smooth and round circumference which permits the use of compression type cord grip fittings to provide a watertight means of conductor entrance into a junction box; and (5) usability with presently available separable connectors for making wiring terminations.

Commentary:

In Sec. 6.4 of this document, Power and Control Tray Cable was identified as a candidate PV wiring system. In that Section, the applicable use-restrictions specified in the NEC are pointed out together with the guidelines that could be used to establish qualification of this wiring system for PV use.

#### 8.4 Open Conductors

Open conductors (conductors not contained within a raceway or within an outer sheath of a cable or other wiring system) were found to be used quite extensively for making interconnections between modules. Stranded conductors having cross-linked insulation rated for wet locations, Type XHHW were employed. The conductors were terminated in separable connectors.

The reasons expressed by manufacturers for using open conductors included: (1) easy to install; and (2) can be used with readily available separable connectors which provide a watertight means of conductor entrance into the junction box.

Commentary:

As discussed in Secs. 5.17 and 5.18 of this document, open general-use type conductors (conductors not contained within an outer sheath or within a raceway) are permitted to be used in two types of systems: (1) Article 320- Open Wiring On Insulators; and (2) Article 324 - Concealed Knob-and-Tube Wiring and only in special circumstances. In other than these two systems, open conductors are limited to factory wiring integral with appliances.

Open wiring on insulators is permitted only in industrial and agricultural applications. Concealed knob and tube wiring systems can be used only for extensions of existing installations or elsewhere only if special permission is granted by the inspection authority having jurisdiction. The permitted use specified in Section 324-3 that is applicable to PV applications is Item 2 of that section which restricts concealed knob and tube wiring to only unfinished attics and roof spaces. Because of this restriction, concealed knob and tube wiring is limited to arrays employing integral-mounted modules where the wiring is usually located in an attic space.

Because of the absence of a raceway or outer sheath, special considerations have to be given to protection of the conductors against physical damage and to provision of support for the conductors in both open wiring systems in accordance with Articles 320 and 324. In electrical equipment and appliances, these aspects are covered by product safety standards.

#### 8.5 Wiring Terminations and Junction Boxes

Modules having a means for terminating the circuit conductors at wiring terminals or by splicing connections to integral leads were provided with either a plastic or metallic junction box having a gasketed cover. The junction boxes were secured to modules by adhesive. Wiring terminals consisted of either a: (1) terminal block having wire binding screws and terminal plates; or (2) stud-and-nut type terminals mounted to a base of insulating material. Some modules contained blocking and by-pass diodes within the junction box.

Some manufacturers utilized supplemental sealing methods to provide additional protection against corrosion of terminal connections. This included the application of spray-on conformal coatings and the use of potting compounds. These materials are applied after field wiring connections are made.

#### Commentary:

The types of wiring terminals noted above are in accordance with the guidelines contained in Sec. 7.2 of this document covering Terminations. These types of wiring terminals also fulfill the considerations contained in Sec. 4.5 of this document covering Ease of Installation, Inspection and Maintenance.

Constructions requiring the application of conformal coatings or potting materials after the installation of wiring are not recommended as this would hamper inspection and serviceability of the system. This is discussed in Sec. 4.5 of this document covering Ease of Installation, Inspection and Maintenance.

## 9. SUMMARY

An overall assessment of the permitted uses, use-restrictions, advantages and disadvantages of nineteen wiring systems described in the NEC revealed that there are five that can be considered as candidate wiring systems for use in PV applications. However, some of these wiring systems were found to have use-restrictions which may not allow their acceptance by the inspection authorities in some PV applications.

Considerations were established that need to be addressed in any proposed revisions of the NEC for the purpose of qualifying these candidate wiring systems for uses other than those presently indicated. Revisions of the NEC expanding the permitted uses of a specific wiring system would necessitate that all brands of that wiring system equipment have the necessary properties to meet the expanded uses. This may not be possible for all manufacturers if changes in materials are necessary. In such a case, it may be feasible for manufacturers who wish to qualify their product for expanded uses, to submit their product to investigation for compliance with the added requirements. The products which meet the requirements could be identified as also suitable for the expanded uses.

An outline of a proposal for investigation of solar PV cable was established. This outline, which describes the requirements in detail or references other UL Standards, is intended to be used as a guide in judging the safety of the construction and performance of PV cable to verify that it will meet the conditions of use expected in PV installations.

The wiring termination methods permitted by the NEC for field connections are identified and described. Although each of these methods permitted by the NEC may be usable in PV arrays, certain methods have characteristics that will enhance installation, inspection and maintenance of the PV system.

An outline of a proposal for investigation of connectors for use in PV wiring systems was established. This outline contains detailed safety requirements covering construction and performance of separable connectors that are intended to be used in accordance with the provisions contained in Secs. 690-32 and 33 of the NEC. Presently available Listed PV connectors have been investigated and found to comply with the requirements.

## A P P E N D I X    A

### OUTLINE OF PROPOSAL FOR INVESTIGATION OF CONNECTORS FOR USE IN PHOTOVOLTAIC WIRING SYSTEMS

#### 1. Introduction

1.1        This outline contains provisions that are intended to be used as a guide in the investigation of connectors for use in photovoltaic wiring systems. It should be understood that these provisions are not to be considered complete or final. Additional tests or provisions may be necessary if features of construction or use are present that have not been anticipated by these provisions.

#### 2. Use Conditions and References

2.1        Taking into consideration the environmental and use conditions that prevail in photovoltaic array applications, this outline specifies the properties of photovoltaic connectors together with the requirements for evaluation of these properties. These requirements are either described in detail or referenced to existing UL Standards, UL Bulletins or other documents. The UL Standards, UL Bulletins and other documents referenced in this text include the following:

- (1) Attachment Plugs and Receptacles, UL 498 - 1981.
- (2) Flat-Plate Photovoltaic Modules and Panels, Proposed First Edition of the Standard, UL 1703 - March, 1984.
- (3) Polymeric Materials - Short Term Property Evaluations, UL 746A - 1978.
- (4) Polymeric Materials - Long Term Property Evaluations, UL 746B - 1979.
- (5) Polymeric Materials - Use In Electrical Equipment Evaluations, UL 746C - 1978.
- (6) Standard Test Method for Comparative Tracking Index of Electrical Insulation Materials, ASTM D3638-1977.
- (7) Tests For Flammability Of Plastic Materials for Parts In Devices And Appliances, UL 94 - 1980.
- (8) Wire Connectors For Use With Aluminum Conductors, UL 486B - 1982.
- (9) National Electrical Code.

### 3. Scope

3.1 These provisions cover cable connectors rated 600 V dc or less and intended for on-site interconnection of photovoltaic modules and other array components in accordance with the National Electrical Code.

### 4. Glossary

4.1 For the purpose of this outline, the following definitions apply.

4.2 Array - A mechanically integrated assembly of photovoltaic modules and panels, together with support structure and foundation, tracking, thermal control, and other components, if used, to form a direct-current power-producing unit.

4.3 Module - The smallest complete, environmentally protected assembly of solar cells, optics and other components, exclusive of tracking, designed to generate direct-current power under sunlight.

4.4 PV - Denotes the word "photovoltaic."

### 5. Construction

#### 5.1 Insulating Materials

5.1.1 Insulating Materials employed in a connector shall have properties which will not be adversely affected by the environmental conditions and electrical stress expected in PV applications. These properties include those described in Pars. 5.1.2-5.1.7.

#### Resistance to Ignition:

5.1.2 The material shall be capable of withstanding abnormally high temperatures resulting from fault conditions that cause the connector to carry current in excess of its rated current or other conditions such as increased contact resistance within the connector resulting in reduced current-carrying capability of the connector. For compliance with this provision, the Hot Wire Ignition property of the material, as determined by the method described in UL 746A, shall comply with the minimum value specified in Table 5.1.1.

High Current Arc Resistance:

5.1.3 The material shall be capable of withstanding arcing on its surface during service of the connector when the contacts make and break an electrical load. For compliance with this provision, the connector shall withstand the Resistance To Arcing Test specified in Par. 6.8.1 and 6.8.2.

Comparative Tracking Index (CTI):

5.1.4 The material shall be capable of resisting surface tracking when: (1) under electrical stress; and (2) exposed to surface moisture and contamination. For compliance with this provision, the Comparative Tracking Index of the material, as determined by the method described in the Standard Test Method for Comparative Tracking Index of Electrical Insulation Materials, ASTM D3638-1977, shall comply with the minimum value specified in Table 5.1.1.

Temperature Index:

5.1.5 The material shall not demonstrate significant degradation of mechanical and electrical properties when subjected to the temperatures expected in PV applications. For compliance with this provision, the Temperature Index of the material, as determined by the method described in UL 746B, shall comply with the minimum value specified in Table 5.1.1.

Water Absorption:

5.1.6 The material shall be capable of resisting high moisture atmospheric conditions without affecting the dimensional integrity of the connector to the extent that critical spacings are reduced resulting in excessive leakage current or a breakdown in dielectric strength. For compliance with this provision, the Permanence of the material, as determined by the method described in UL 746A, shall comply with the maximum value specified in Table 5.1.1.

Resistance to Solar Radiation:

5.1.7 The material shall not demonstrate significant degradation of flammability and physical properties when exposed to ultraviolet radiation. Compliance with this provision is to be determined by subjecting samples of the material to an exposure of ultraviolet light with intermittent water spray in accordance with the method described in Sec. 27 of UL 746C.

TABLE 5.1.1

MATERIAL PROPERTY REQUIREMENTS<sup>a</sup>

| Property                                           | Units                        | Flammability Classification <sup>b</sup> |                 |                 |                 |                 |
|----------------------------------------------------|------------------------------|------------------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                                    |                              | 94-5V                                    | 94V-0           | 94V-1           | 94V-2           | 94HB            |
| Hot Wire Ignition                                  | Min. No. of Sec. to Ignition | 10                                       | 10              | 15              | 15              | 30              |
| Comparative Tracking Index (CTI)                   | -                            | 250                                      | 250             | 250             | 250             | 250             |
| Temperature Index, Elect. & Mechanical With Impact | Min. C°                      | 90 <sup>c</sup>                          | 90 <sup>c</sup> | 90 <sup>c</sup> | 90 <sup>c</sup> | 90 <sup>c</sup> |
| Permanence                                         | Max. % Change                | 2                                        | 2               | 2               | 2               | 2               |

- <sup>a</sup> - The material shall be evaluated using specimens of the thickness used in the connector or 1/8 in. (3.2 mm) thickness.
- <sup>b</sup> - Flammability Classification of the material under consideration in accordance with the test methods described in UL 94.
- <sup>c</sup> - Or 20°C above temperature rating of connector, whichever is greater.

5.2 Accessibility of Live Hazardous Parts

5.2.1 Live parts that present a shock hazard, including contacts on both the male and female pieces of a connector shall be enclosed or recessed to guard against inadvertent contact with hazardous live parts. This will be evaluated by applying the accessibility probe requirements specified in Sec. 15 of UL 1703.

### 5.3 Corrosion Protection

5.3.1 Except for machine screws, washers, nuts, and stainless steel parts, iron and steel parts shall be capable of withstanding the effects of exposure to moisture expected during service conditions without adversely affecting the mechanical properties of the parts. For compliance with this provision, the corrosion protection means shall be in accord with that stipulated in Par. 18.10 of UL 498.

### 5.4 Current-Carrying Parts

5.4.1 Current-carrying parts shall be constructed of materials which have suitable corrosion resistive and conductive properties. Compliance is determined according to the provisions of Pars. 7.1 and 7.2 of UL 498.

### 5.5 Securement

5.5.1 To reduce the risk of fire hazard that may result from arcing at loose connections, a connector shall be provided with a means to ensure positive electrical connection.

#### Live Parts:

5.5.2 With reference to Par. 5.5.1, a connector shall be constructed to withstand expected forces during normal use without loosening of live parts. Compliance is determined according to the provisions of Pars. 7.3 and 7.4 of UL 498.

#### Engagement:

5.5.3 The provision of Par. 5.5.1 necessitates that the PV connector be provided with a latch or the equivalent means to maintain positive engagement between mating portions of the connector.

#### Conductor Termination:

5.5.4 A connector intended to accommodate aluminum and copper conductors shall comply with the requirements contained in UL 486B.

## 5.6 Grounding Means

5.6.1 To reduce the risk of electric shock, the grounding member, if provided, shall: (1) be the first to make contact and the last to break contact; and (2) be constructed in accordance with the requirements specified in Pars. 8.1-8.3, 8.5-8.7, 8.14 and 8.16 of UL 498.

## 5.7 Polarization

5.7.1 To reduce the risk of electric shock and fire, a connector shall be constructed so as to prevent a portion of the connector from being connected to a mating portion of unlike polarity, if such is an improper connection.

5.7.2 The provision of Par. 5.7.1 necessitates that the construction of connectors incorporate an obstruction or the equivalent to provide: (1) polarization of multipole connectors; and (2) prevention of a portion of a single pole connector from being inserted into and making electrical contact with a mating portion of a connector of unlike polarity, if such is an improper connection.

## 5.8 Noninterchangeability

5.8.1 To reduce the risk of electric shock and fire a connector shall be constructed so as to prevent misconnection of PV source circuit components to other electricity systems.

5.8.2 Generally, provision of Par. 5.8.1 necessitates that a connector be provided with a contact configuration which is other than those described in Figs. 81.1-81.38 of UL 498.

## 5.9 Spacings

5.9.1 Spacings specified in Sec. 12 of UL 498 shall be provided to reduce the risk of electric shock which may result from the effects of: (1) changing characteristics of insulating materials; (2) condensation of water; (3) contamination of insulating materials caused by pollution; and (4) transient voltages. These spacings shall be provided between uninsulated live parts of opposite polarity and between an uninsulated live part and a dead-metal part that is likely to be grounded or exposed to contact by persons.

## 6. Performance

### 6.1 General

6.1.1 For each of the following tests, the connector is to be assembled to a length of cable as intended in accordance with the manufacturer's instructions.

Exception: Accelerated aging of gaskets and seals test specified in Par. 6.3.1-6.3.3.

### 6.2 Body materials

6.2.1 Connector body compounds shall not demonstrate significant deterioration of physical properties as a result of aging.

6.2.2 With reference to Par. 6.2.1, rubber and PVC compounds shall be subjected to accelerated aging tests specified in Sec. 31 of UL 498. Other body materials shall comply with the requirements contained in Par. 5.1.5 and in UL 746C.

### 6.3 Accelerated Aging of Gaskets and Seals

6.3.1 To minimize the risk of electric shock, gaskets and seals used to provide a weather tight seal for PV connectors shall exhibit suitable physical properties.

6.3.2 The test procedure for determining whether a gasket or seal complies with the requirement in Par. 6.3.1 depends upon the material of which it is composed, its size and shape, the mode of application in the connector, and other factors. Among the tests applied are visual inspection for determination of cracks, deformation, etc. - after artificial aging, as well as comparison of hardness, tensile strength and elongation before and after artificial aging.

6.3.3 With reference to Pars. 6.3.1 and 6.3.2, a component of rubber or neoprene, if tested to compare its strength and elongation before and after artificial aging, is acceptable if these properties are found to be not less than the minimum values specified in Table 6.3.1, corresponding to the temperature of the gasket or seal obtained during the Temperature Test specified in Sec. 6.5. If it is impractical to measure these properties due to the size and shape of the seal, the acceptability may be determined by one or more of the other means mentioned in Par. 6.3.2.

TABLE 6.3.1

ARTIFICIAL-AGING TEST

| Temperature on<br>Component During<br>Temperature Test |                | Artificial-Aging<br>Procedure                                                                                                                                                                                    | Minimum Acceptable<br>Percent of Unaged<br>Value For Samples |                 |
|--------------------------------------------------------|----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------|-----------------|
| C°                                                     | F°             |                                                                                                                                                                                                                  | Tensile<br>Strength                                          | Elong-<br>ation |
| 60 or<br>less                                          | 140 or<br>less | Aged in oxygen bomb for 96 h at<br>70.0 ± 1.0°C (158.0 ± 1.8°F) and<br>300 ± 10 psi gauge (2070 ± 70 kPa)                                                                                                        | 60                                                           | 60              |
| 61-75                                                  | 142-167        | Aged in oxygen bomb for 168 h at<br>80.0 ± 1.0°C (176.0 ± 1.8°F) and<br>300 ± 10 psi gauge (2070 ± 70 kPa)<br>and in air bomb for 20 h at<br>127.0 ± 1.0°C (260.6 ± 1.8°F) and<br>80 ± 3 psi gauge (551 ± 20 Pa) | 50                                                           | 50              |
| 76-90                                                  | 169-194        | Aged in full-draft, air-circulating<br>oven for 168 h at 121.0 ± 1.0°C<br>(249.8 ± 1.8°F)                                                                                                                        | 50                                                           | 50              |
| 91-105                                                 | 196-221        | Aged in full-draft, air-circulating<br>oven for 168 h at 136.0 ± 1.0°C<br>(276.8 ± 1.8°F)                                                                                                                        | 50                                                           | 50              |

#### 6.4 Insulation Resistance

6.4.1 The insulation resistance of insulating materials shall comply with the requirements contained in Sec. 32 of UL 498 to reduce the risk of electric shock resulting from excessive leakage currents.

#### 6.5 Temperature Test

6.5.1 An insulating material shall not exhibit significant degradation of electrical and mechanical properties when exposed to elevated temperatures normally encountered in PV applications for extended periods of time.

6.5.2 Compliance with the provision of Par. 6.5.1 necessitates that a temperature test in accordance with the method described in Secs. 33 and 45 of UL 498 be conducted. In consideration of the end-use ambient associated with PV applications and the temperature index for insulating materials specified for connectors in Table 5.1.1, the temperature limits specified in Table 6.5.1 shall be applied.

TABLE 6.5.1  
MAXIMUM TEMPERATURE

| Part, Material, or Component                                | Temperature       |     |
|-------------------------------------------------------------|-------------------|-----|
|                                                             | °C                | °F  |
| 1. Insulating materials:                                    |                   |     |
| Polymeric                                                   | (a)               | (a) |
| Varnished cloth                                             | 85                | 185 |
| Fiber                                                       | 90                | 194 |
| Laminated phenolic composition                              | 125               | 257 |
| Molded phenolic composition                                 | 150               | 302 |
| 2. Sealing compound                                         | (b)               | (b) |
| 3. Field wiring terminals                                   | 60                | 140 |
| 4. Insulating conductors                                    | Rated Temperature |     |
| 5. External surface which may contact combustible materials | 90                | 194 |

Notes for Table 6.5.1

- (a) The relative thermal index of the polymeric material, less 20°C (36°F). [The relative thermal index describes the maximum temperature, for a specific time, at which a material can be expected to retain its characteristics.]
- (b) The maximum sealing compound temperature, when corrected to a 40°C (104°F) ambient temperature, is to be 15°C (27°F) less than the softening point of the compound as determined by the Standard Test Method for Softening Point by Ring and Ball Apparatus, ASTM E28-1967 (1977).

6.5.3 Material and component temperatures are to be determined for an ambient temperature of 40°C. The ambient temperature may be in the range of 10°C to 55°C, in which case each observed temperature shall be corrected by the addition (if the ambient temperature is below 40°C) or subtraction (if the ambient temperature is above 40°C) of the difference between 40°C and the observed ambient temperature.

#### 6.6 Dielectric Voltage Withstand Test

6.6.1 To reduce the risk of electric shock, the insulation and spacings between live parts and accessible conductive parts and between live parts and exposed nonconductive surfaces shall withstand the application of the dielectric voltage in accordance with the test requirements specified in Sec. 25 of UL 1703.

#### 6.7 Overload Test

6.7.1 A connector shall be capable of interrupting a direct-current circuit without creating a risk of electric shock. This is evaluated by the tests outlined in Sec. 44 of UL 498.

#### 6.8 Resistance to Arcing Test

6.8.1 The insulating materials employed in a connector shall be capable of withstanding arcing likely to occur on the material surface during normal service without creating a risk of fire or electrical shock.

6.8.2 For compliance with the provision of Par. 6.8.1, a Resistance To Arcing Test in accordance with Sec. 46 of UL 498 shall be conducted. The results are acceptable if there is no ignition of the material and there is no permanent carbon conductive path on the material surface as judged by the application of a dielectric voltage withstand potential in accordance with the method described in Sec. 25 of UL 1703.

#### 6.9 Cable and Conductor Securement Tests

6.9.1 A connector shall incorporate a reliable means for securement of the PV cable and connection of the conductors. The securement and connection means shall be capable of withstanding the forces that might be experienced during normal and reasonably foreseeable abuse during installation and routine servicing of a PV module without resulting in damage to the cable securement or conductor connection means. See Pars. 6.9.2 and 6.9.3.

##### Cable Strain Relief:

6.9.2 Compliance with the provision of Par. 6.9.1 necessitates that the cable securement means be subjected to a 20 lb pull in accordance with the Strain Relief Test specified in Sec. 22 of UL 1703.

Conductor Secureness:

6.9.3 Compliance with the provision of Par. 6.9.1 necessitates that a crimped connection of a conductor to an internal member of a connector be subjected to the Conductor Secureness Test specified in Sec. 40 of UL 498.

6.10 Mechanical Abuse Tests

6.10.1 A connector body shall be capable of withstanding reasonably foreseeable mechanical abuse which may be encountered during installation and routine servicing of a PV module. Compliance with this requirement will be judged by conducting the Crushing and Impact Tests outlined in Pars. 6.10.2 and 6.10.3. These tests shall not produce conditions that would: (1) allow accessibility of hazardous live parts as determined by the probe requirements specified in Par. 5.2.1; and (2) permit entrance of water on uninsulated live parts.

Crushing Test:

6.10.2 For compliance with the crushing test provisions specified in Par. 6.10.1, a 75 lb crushing force is to be applied to the connector body in accordance with the method described in Sec. 36 of UL 498.

Impact Test:

6.10.3 For compliance with the impact test provisions specified in Par. 6.10.1, the connector body shall be subjected to a 5 ft lb impact in accordance with the method described in Sec. 29 of UL 1703.

6.11 Exposure to Water Spray

6.11.1 To reduce the risk of electric shock, a connector shall be constructed to exclude a beating rain.

6.11.2 Compliance with the provisions of Par. 6.11.1 shall be judged by conducting the Exposure to Water Spray Test in accordance with the method described in Sec. 31 of UL 1703. The test shall not result in water on uninsulated live parts. Immediately following this test, the connector shall comply with the dielectric voltage withstand test, Sec. 26, and the leakage current test specified in Sec. 21 of UL 1703.

## 6.12 Temperature Cycling

6.12.1 To reduce the risk of electric shock, the integrity of a connector body and the contact resistance within the connector shall not be adversely affected when exposed to wide temperature fluctuations expected in the environments associated with PV array installations.

6.12.2 Compliance with the provision of Par. 6.12.1 will be determined by subjecting the connector to 200 cycles of temperature changes, each cycle consisting of a transition from -40°C to 90°C in accordance with the method described in Sec. 33 of UL 1703. After completion of these exposures, the connector shall: (1) not permit access to live parts that may result in a risk of electric shock; (2) withstand the application of the dielectric voltage specified in Par. 6.6.1; and (3) comply with the leakage current requirements specified in Sec. 21 of UL 1703.

## 6.13 Humidity

6.13.1 To reduce the risk of electric shock, electrical properties of insulating materials used in connectors and the contact resistance within the connector shall not be adversely affected when exposed to wide temperature fluctuations under high humidity conditions.

6.13.2 Compliance with the provision of Par. 6.13.1 will be determined by subjecting the connector to 10 cycles of humidity-freezing exposures, each exposure consisting of a transition from 85°C at 85 percent RH to -40°C. The details of the test method shall be in accordance with the conditions specified in Sec. 34 of UL 1703. After completion of these exposures, the connector shall: (1) not permit access to live parts that may result in risk of electric shock; (2) withstand the application of a dielectric voltage withstand test in accordance with Par. 6.6.1; (3) comply with the temperature test requirements specified in Par. 6.5.1-6.5.2; and (4) comply with the leakage current requirements specified in Sec. 21 of UL 1703.

## 7. Markings

7.1 A connector shall be marked in accordance with the provisions of Sec. 66 of UL 498. The content of these markings shall include the following and unless otherwise noted, the markings shall be located on the connector:

- (1) Manufacturer's name or trademark.
- (2) Electrical rating on the receptacle portion of the connector.

- (3) Catalog number or equivalent designation, either on the: (1) connector; (2) shipping carton; or (3) information sheet packaged with the connector.
- (4) The letters "PV" or the equivalent designation for identification of the connector for photovoltaic use, either on: (1) the connector; (2) the shipping carton; or (3) the information sheet packaged with the connector.
- (5) Information specifying the type and outside diameter of the cable with which the connector is intended to be used. This information shall be provided on either the shipping carton or on an information sheet packaged with the connector.
- (6) If a connector is intended to be assembled to a cable by the use of a specific tool, the tool designation together with instructions necessary for proper assembly shall be marked on: (1) the connector; (2) the shipping carton; or (3) the information sheet packaged with the connector.
- (7) If the connector is not acceptable for accommodating aluminum wire, or if the connector manufacturer intends the use of only copper wire, the shipping carton or sheet packaged with the connector shall contain the following marking:
  - (a) "Notice - Use only copper or copper-clad wire with this connector," or
  - (b) "Notice - Connect only copper or copper-clad wire to this connector."

Exception: If the above marking or the abbreviated marking of Item 8 is provided on connector itself.

- (8) The marking specified in Item 7 may be abbreviated as follows, if provided on the connector itself:
  - (a) "Use copper wire only,"
  - (b) "Cu wire only,"
  - (c) "Use copper or copper-clad wire only," or
  - (d) "Cu and Cu-clad wire only."

A P P E N D I X    B

OUTLINE OF PROPOSAL FOR INVESTIGATION OF  
SOLAR PHOTOVOLTAIC CABLES

1. Introduction

1.1 This outline contains provisions that are intended to be used as a guide in the investigation of solar photovoltaic cables. It should be understood that these provisions are not to be considered complete or final. Additional tests or construction stipulations may be necessary if features of cable construction or use conditions are present that have not been anticipated by these provisions. Certain tests included herein may be omitted on the basis of previous evaluations of the particular materials.

2. Use Conditions and References

2.1 The environmental and use-conditions associated with installations of photovoltaic modules exposes the photovoltaic system cable to: (1) weather, which includes sunlight and rain; (2) wide temperature fluctuations; (3) mechanical abuse during installation, such as rubbing over sharp edges and being pulled through bored holes in roof rafters; or (4) handling by the servicemen during module replacement. Taking into consideration these environmental and use-conditions, this outline specifies the provisions for photovoltaic system cable together with the method for evaluation of these properties. These requirements are either described in detail or a reference to existing UL Standards or UL Bulletins is provided. The UL Standards and UL Bulletins referenced in this text include the following:

- (1) Flexible Cord and Fixture Wire, UL 62 - 1982.
- (2) Electrical Outlet Boxes and Fittings, UL 514 - 1979.
- (3) Nonmetallic-Sheathed Cables, UL 719 - 1979.
- (4) Rubber-Insulated Wires and Cables, UL 44 - 1983.
- (5) Thermoplastic-Insulated Underground Feeder and Branch-Circuit Cables, UL 493 - 1983.
- (6) Service-Entrance Cables, UL 854 - 1979.
- (7) Thermoplastic-Insulated Wires and Cables, UL 83 - 1980.

- (8) Type TC Power and Control Tray Cables, Subject 1277, Outline of Proposed Investigation dated December 19, 1980.
- (9) National Electrical Code.

### 3. Scope

2.1 These provisions cover Solar Photovoltaic Cable (Type PV Cable) which is a factory assembly of one or more insulated conductors, with or without a grounding conductor under a nonmetallic jacket. The cable is intended for use in photovoltaic arrays as described in Article 690 of the National Electrical Code covering Solar Photovoltaic Systems and for installation in accordance with Articles 336 and 339 of the NEC. It is expected that No. 16 and 18 AWG conductors will be protected in accordance with their ampacity as indicated in Table 402-5 of the NEC. The cable is rated 600 V or less, 75°C. This temperature is based on the operating temperatures observed on some module constructions.

### 4. Glossary

4.1 For the purposes of this outline, the following definitions apply:

4.1.1 Array - A mechanically integrated assembly of photovoltaic modules and panels, together with the support structure and foundation tracking, thermal control, and other components, if used, to form a direct-current power-producing unit.

4.1.2 Cable - Denotes Solar Photovoltaic Cable included in the scope of this outline.

4.1.3 Module - The smallest complete, environmentally protected assembly of solar cells, optics and other components, exclusive of tracking, designed to generate direct-current power under sunlight.

4.1.4 PV - Denotes the word "Photovoltaic."

### 5. Construction

#### 5.1 Conductors

5.1.1 The conductors shall be made of bare or coated annealed copper in the following sizes: (1) No. 18 AWG-1 AWG employed in multi-conductor cable, and (2) No. 14 AWG-1 AWG employed in single-conductor cable.

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5.1.2 If a grounding conductor is provided, it shall not be smaller than the circuit conductors.

## 5.2 Insulation

5.2.1 The conductor insulation shall be capable of withstanding exposure to moisture and the temperatures which may be encountered in PV environments without adversely affecting its mechanical and electrical properties.

5.2.2 For compliance with the provisions of Par. 5.2.1, the individual circuit conductors shall be insulated in accordance with the requirements contained in UL 44 or UL 83, rated 75°C and having wet locations insulation ("W" in the type letters such as THW, THWN, RHW, and XHEW). Conductors employing other insulation, or wall thicknesses may be used if their acceptability is determined by investigation.

## 5.3 Conductor Assembly

5.3.1 The construction of the cable shall provide a suitable level of mechanical protection to allow installation of the cable and servicing of the PV module without damage to the cable. The provisions of Pars. 5.3.2-5.3.4 cover this.

5.3.2 The individual conductors of a cable shall be of the size and temper as specified in the appropriate Standard for Thermoplastic-Insulated Wires, UL 83 or the Standard For Rubber-Insulated Wire and Cables, UL 44. If the individual conductors are stranded, the stranding shall be as specified in UL 44 or UL 83 as appropriate.

5.3.3 The length of the lay of the cabled conductors shall comply with the specifications contained in Table 5.3.1. The use of fillers is optional.

5.3.4 The cabled assembly may be enclosed in a braid, tape, or other binder. Individual groups may employ a covering consisting of the same jacket material and temperature rating as the overall jacket specified in Sec. 5.5 providing that the thickness of the covering complies with the minimum values specified in Table 5.3.2.

TABLE 5.3.1

LENGTH OF LAY OF CABLED CONDUCTORS

| <u>Number of Circuit<br/>Conductors in Cable</u> | <u>Maximum Acceptable Length of Lay</u>                                                                                                                                                                                                        |
|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2                                                | 30 times conductor diameter <sup>a</sup>                                                                                                                                                                                                       |
| 3                                                | 35 times conductor diameter <sup>a</sup>                                                                                                                                                                                                       |
| 4                                                | 40 times conductor diameter <sup>a</sup>                                                                                                                                                                                                       |
| 5 or more                                        | 15 times the calculated overall diameter of<br>the assembly but, in a multiple-layer cable,<br>the length of lay of the conductors in each<br>of the inner layers is not specified<br>(governed by the construction of the cabling<br>machine) |

<sup>a</sup> - "Conductor diameter" is the calculated diameter of the  
largest individual, finished insulated conductor in the  
cable.

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TABLE 5.3.2

THICKNESS OF GROUP COVERING

| Calculated Diameter of Round<br>Assembly Under Group<br>Covering, Inches (mm) | Minimum<br>Acceptable<br>Average<br>Thickness,<br>Mils (mm) | Minimum<br>Acceptable<br>Thickness<br>At Any Point,<br>Mils (mm) |
|-------------------------------------------------------------------------------|-------------------------------------------------------------|------------------------------------------------------------------|
| 0.425 or less (10.80 or less)                                                 | 15 (0.38)                                                   | 12 (0.30)                                                        |
| Over 0.425 but not over 0.700<br>(over 10.80 but not over 17.79)              | 30 (0.76)                                                   | 24 (0.61)                                                        |
| Over 0.700 but not over 1.500<br>(over 17.78 but not over 38.10)              | 45 (1.14)                                                   | 36 (0.91)                                                        |

#### 5.4 Cable Assembly

5.4.1 The construction of a cable shall allow the use of round cable connectors which provides a water tight securement means of a cable to a junction box.

5.4.2 The provision specified in Par. 5.4.1 necessitates that the circumference of a cable containing two or more conductors be smooth and round. Fillers shall be provided in a cable as needed to make the finished cable round. Fillers in a jacketed cable may be integral with or separate from the jacket. If integral with the jacket, both filler and jacket shall be readily separable from the underlying cable assembly. Fibrous filler materials that are not inherently resistant to moisture shall be rendered so. Treatment with paraffin is acceptable in a jacketed cable but not in a cable with a layered outer covering.

#### 5.5 Jacket

5.5.1 The jacket shall be resistant to the effects of weathering and shall be sufficiently thick to provide mechanical protection for the conductor. This necessitates compliance with requirement contained in Par. 5.5.2. Also, see Sections 8.5 and 8.6

5.5.2 An extruded jacket of nonmetallic material having thicknesses as specified in Tables 5.5.1 and 5.5.2 shall be applied to multi-conductor and single-conductor cables respectively.

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TABLE 5.5.1

THICKNESS OF JACKET FOR MULTI-CONDUCTOR PV CABLE

| Calculated Diameter of Round Assembly<br>Under Jacket, Inches (mm) | Minimum Acceptable<br>Thickness of Jacket,<br>Mils (mm) |              |
|--------------------------------------------------------------------|---------------------------------------------------------|--------------|
|                                                                    | Average                                                 | At Any Point |
| 0.425 or less (10.80 or less)                                      | 45 (1.14)                                               | 36 (0.91)    |
| Over 0.425 but not over 0.700<br>(over 10.80 but not over 17.78)   | 60 (1.52)                                               | 48 (1.22)    |
| Over 0.700 but not over 1.500<br>(over 17.78 but not over 38.10)   | 80 (2.03)                                               | 64 (1.63)    |
| Over 1.500 but not over 2.250<br>(over 38.10 but not over 57.15)   | 110 (2.79)                                              | 88 (2.24)    |
| Over 2.250 but not over 3.000<br>(over 57.15 but not over 76.20)   | 140 (3.56)                                              | 112 (2.84)   |
| Over 3.000 (over 76.20)                                            | 140 (3.56)                                              | 112 (2.84)   |

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TABLE 5.5.2

THICKNESS OF INTEGRAL INSULATION AND  
JACKET ON SINGLE CONDUCTOR PV CABLE

| AWG Size of<br>Conductor | Minimum Acceptable Thickness, Mils (mm) <sup>a</sup> |                       |
|--------------------------|------------------------------------------------------|-----------------------|
|                          | Average of "PVC"                                     | At Any Point of "PVC" |
| 14-10                    | 60 (1.52)                                            | 54 (1.37)             |
| 8-2                      | 80 (2.03)                                            | 72 (1.83)             |
| 1                        | 95 (2.41)                                            | 86 (2.18)             |

<sup>a</sup> - The method of preparing specimens, taking the measurements, and determining compliance shall be as specified in the Standard for Thermoplastic-Insulated Wires, UL 83.

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## 5.6 Direct Burial

5.6.1 A cable used in direct burial applications shall resist the effects of mechanical abuse that may occur during installation of the cable.

5.6.2 Compliance with the provisions of Par. 5.6.1 necessitates that a cable marked "Direct Burial," "Dir Burial," "Dir Bur," or other equivalent abbreviation in accordance with Par. 6.1.8 be subjected to the Crushing Test specified in Pars. 8.6.9-8.6.11.

## 6. Marking

6.1 The items specified in Pars. 6.1.1-6.1.8 shall be printed on the surface of the nonmetallic jacket at intervals no longer than 24 in. (610 mm) by means of durable ink or raised or indented lettering.

6.1.1 The name of the cable manufacturer, his trade name for the product, or both, or any other acceptable distinctive marking by means of which the organization responsible for the product can readily be identified. If the organization that is responsible for the product is different from the actual manufacturer, both of the responsible organization and the actual manufacturer shall be identified by name or by acceptable coding such as by trade name, trademark, the assigned electrical reference number or the assigned combination of colored marker threads. The meaning of any coded identification shall be made available. A private labeler may also be identified. The responsible organization's distinctive colored marker thread(s) located in the cable core shall be provided in addition to ink printing unless the printing has been found to be durable by means of the test specified in the Standard for Thermoplastic-Insulated Wires (UL 83). If the organization responsible for the product produces Type PV cable in more than one factory, an acceptable identification of the factory shall be included. In the case of a colored thread or threads, the ply or the material of one or more of the threads used at each factory shall be different from the ply or material of the same color thread or threads used at every other factory. The organization responsible for the products shall make available the meaning of the different plies and materials.

6.1.2 AWG Size of Conductors - Not required if each conductor is marked with its size.

6.1.3 "600 V."

6.1.4 "Type PV."

6.1.5 Conductor Type Designation - If the circuit conductors are of a type defined by the National Electrical Code but are unmarked, the conductor type letters are required on the surface of the jacket. If NEC type conductors are used and are so marked, no reference to temperature rating and/or the conductor type letter is needed on the surface of the jacket.

6.1.6 The cable shall be marked 75°C wet if the conductors are not of a type defined by the National Electrical Code. A cable containing conductors with more than one temperature rating shall be assigned the lowest temperature rating of any of the constituent conductors (75°C minimum).

6.1.7 Additional markings, such as "Art. 690," etc. are not required but may be added provided they do not mislead. In this context "VW-1," "Gasoline-Resistant," and other references to conductor designations other than the type letters that are not acceptable on the individual conductors, and as part of the tag marking are not acceptable on the overall jacket.

6.1.8 The cable may be marked "Direct Burial" or "Dir Burial," "Dir Bur" or another equivalent abbreviation if the cable complies with Pars. 5.6.1 and 5.6.2.

7. Conductor Identification

7.1 Grounding circuit conductors shall be identified in accordance with the color code requirements contained in the NEC so that they can be distinguished from one another and from other circuit conductors. This requires that the conductor be color coded in accordance with Pars. 7.2-7.4.

Grounded Conductor:

7.2 If only one conductor is intended to be a grounded circuit conductor, it shall be finished white or natural grey throughout the entire length and circumference of the insulation. Additional conductors intended to be grounded circuit conductors shall be finished white and shall have either: (1) numbers spaced no more than 3 in. (76 mm) apart; or (2) one or more unbroken straight or helical stripes that contrast with white, that are not green and that occupy a total width of 5-70 percent of the calculated circumference of the finished outer surface of the conductor and no less individual width than 5 percent of the calculated circumference of the finished outer surface of the conductor.

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Grounding Conductor:

7.3 A grounding conductor, if insulated, shall be fully insulated and shall be green for its entire length and circumference except that one or more unbroken yellow stripes, either straight or helical, occupying a total width of 5-70 percent of the calculated circumference of the finished outer surface of the conductor and no less individual width than 5 percent of the calculated circumference of the finished outer surface of the conductor.

Other Conductors:

7.4 A finished conductor intended for other than a grounded or grounding conductor shall be of a color other than and in contrast with white, grey, green, or a combination of yellow and green and shall not have a stripe or stripes of white or green.

8. Performance

8.1 Physical properties.

8.1.1 Cable compounds shall have physical properties which will not degrade appreciably during the expected life of the cable.

8.1.2 For compliance with the provisions of Par. 8.1.1, the tensile strength and elongation of the jacket, unaged and after aging, shall be determined to verify compliance with the applicable requirements for compounds of the specified temperature rating as given in UL 62.

8.2 Flexibility

8.2.1 A cable employing thermoplastic insulated conductors and/or jacket materials shall be capable of being flexed under wide temperature fluctuations without significantly affecting the mechanical properties of the materials. Compliance with this requirement shall be determined by conducting the tests specified in Pars. 8.2.2-8.2.3.

Heat Shock Test:

8.2.2 Cables employing thermoplastic insulated conductor and/or a thermoplastic jacket material shall be subjected to a Heat Shock Test in accordance with the methods described in UL 83. The mandrel diameter used for the complete cable shall be three times the measured outside diameter of the finished cable.

Cold Bend Test.

8.2.3 A cable shall be subjected to a Cold Bend Test in accordance with the method described in UL 83. During this test, samples of a single conductor and the complete cable are to be subjected to a temperature of  $-25^{\circ}\text{C} \pm 2^{\circ}\text{C}$  ( $-13 \pm 3.6^{\circ}\text{F}$ ) for 4 h. The mandrel diameter used for complete cables shall be five times the measured outside diameter of the finished cable.

8.3 Dielectric Voltage Withstand Test

8.3.1 The dielectric strength of a cable shall be capable of withstanding with a reasonable safety factor, the electrical stress produced by the PV system voltage and surge voltages that are encountered in PV array applications without creating a risk of electric shock.

8.3.2 For compliance with the provision of Par. 8.3.1, the insulation of a finished cable shall withstand for 1 min without breakdown, the application of the test potential indicated in Table 8.3.1. Test potentials shall be applied between all circuit conductors, electrically connected together and the outer jacket while immersed in water using a method as described in UL 44 and UL 83.

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TABLE 8.3.1

DIELECTRIC VOLTAGE WITHSTAND TEST POTENTIALS

| <u>Conductor Size</u> | <u>Test Potentials</u> |
|-----------------------|------------------------|
| 18-10 AWG             | 1500 Volts+            |
| 8-2 AWG               | 2000 Volts             |
| 1 AWG                 | 2500 Volts             |

+ - 2000 Volts for THHN, THWN, and THW wires.

8.4 Continuity Test

8.4.1 Cabling shall not result in broken conductors.

8.4.2 Compliance with the requirement contained in Par. 8.4.1 necessitates that the tests outlined in Pars. 9.1-9.5 of UL 719 be conducted.

8.5 Weather Resistance Test

8.5.1 A cable shall be acceptably resistant to a degradation of mechanical properties from the effects of weather which includes exposure to sunlight and rain.

8.5.2 For compliance with the requirement contained in Par. 8.5.1, a finished cable shall be subjected to a Sunlight Resistant Test in accordance with the method described in UL 62.

8.6 Mechanical Abuse Test

8.6.1 A cable shall be acceptably resistant to the effects of reasonably foreseeable mechanical abuse which may be encountered during installation of the cable and servicing of a PV module. This requires consideration to conditions of use such as:  
(1) tensional forces exerted to the cable while being pulled;  
(2) pulling the cable over sharp edges; (3) underground burial of cable in applications of nonroof mounted PV arrays;  
(4) handling the cable in low temperature environments; and  
(5) impacts resulting from falling objects.

8.6.2 Compliance with the requirement contained in Par. 8.6.1 necessitates that the tests outlined in Pars. 8.6.3-8.6.11 be conducted.

Pulling-Through-Joists Tests:

8.6.3 Finished cable shall be subjected to a Pulling-Through-Joists Test in accordance with the methods described in Pars. 40.1-40.9 of UL 854.

Unwinding Tests at Low Temperatures:

8.6.4 Finished cable and the insulated circuit conductors shall be subjected to an Unwinding Test at low temperature in accordance with the method described in Pars. 15.1-15.24 of UL 719.

Abrasion Test:

8.6.5 Finished cable shall be subjected to an Abrasion Test in accordance with the method described in Pars. 19.1-19.5 of UL 719.

Impact Test:

8.6.6 Finished cable and insulated circuit conductors shall be subjected to an Impact Test in accordance with the method described in Pars. 17.1-17.5 of UL 493.

Tension and Elongation Test:

8.6.7 Finished multiple circuit conductor cable shall be subjected to a Tension and Elongation Test in accordance with the method described in Pars. 13.1-13.5 of UL 493.

Pull-Out of Fitting Test:

8.6.8 Cables employing generic classes of jacket material not previously evaluated by a nationally-recognized testing laboratory shall be subjected to a Pull-Out Of Fitting Test in accordance with the methods described in UL 514. During this test, a Listed cable clamp is to be secured to a length of cable and an outlet box as intended. A force of 50 lb is then applied to the cable, attempting to pull the cable out of the clamp. The results are acceptable if the cable remains in the clamp.

Direct Burial Crushing Test:

8.6.9 Finished type PV cable whose overall jacket is surface marked for direct burial as indicated in Par. 6.1.8 shall be capable of withstanding crushing force of 1000 lb without rupture of the: (1) overall jacket; or (2) insulation on any conductor. The test is to be conducted and the results judged as outlined in Pars. 8.6.10-8.6.11.

8.6.10 Three specimens of the finished cable are to be tested. Each specimen is to be placed between a mandrel consisting of right-circular solid steel rod that is 3/4 in. (19 mm) in diameter and a flat horizontal steel plate that is 2 in. (50 mm) wide and a compression machine whose jaws close at a rate of 1/2 in./min (13 mm/min). The specimens, the apparatus, and surrounding air are to be in thermal equilibrium with one another at a temperature of  $24.0 \pm 8.0^{\circ}\text{C}$  ( $75.2 \pm 14.4^{\circ}\text{F}$ ) throughout the test. Each specimen is to be tested separately and is to be subjected to the increasing force between the plate and mandrel until the level indicated in Par. 8.6.9 is reached. The level of force is to be held for 60 sec and then reduced to zero by reversing the machine and separating the plate and mandrel until the specimen is free.

8.6.11 The specimens are to be examined for splitting, tearing, cracking or other rupturing of the overall jacket, and individual conductor jacket and the insulation. Flattening of the jacket(s) and/or insulation without any rupture is to be disregarded. The cable is not acceptable if there is evidence of a rupture in any of the specimens. The results of this test on cable containing a given number and size of the conductors are to be taken as representative of all cables containing one or more conductors of the same size and of all cables containing the same or larger number of conductors of a larger size.

8.7 Flame Test

8.7.1 When exposed to an ignition source, a cable shall exhibit a sufficient flammability characteristic to reduce the risk of fire caused by fire propagating along its length and emission of flaming drops or particles.

8.7.2 Compliance with the provision of Par. 8.7.1 necessitates that a Flame Test in accordance with the method described in Pars. 11.1-11.11 of UL 493 be conducted on finished single conductor cable and on finished multiple conductor cable.

## 8.8 Ease of Stripping

8.8.1 To ensure ease of termination and preparation, the cable jacket and filler materials shall not adhere to the insulation of the conductors or other internal conductor coverings. Compliance with this requirement is to be determined by subjecting a specimen of the cable to the tests described in Pars. 8.8.2-8.8.3.

8.8.2 A specimen of multiple conductor cable approximately 15 in. in length shall have its jacket and filler material cut using a razor blade longitudinally and vertically down to the insulation for approximately 6 in. A second cut around the circumference of the cable is to be made at the end of the first cut. The resulting jacket piece is then to be removed by pulling at right angles away from the cable. Observations are to be made as to whether or not the jacket filler material can be removed without damage to the conductor insulation or other internal conductor coverings. Particles which can be removed by light brushing are acceptable.

8.8.3 The insulation shall be prevented by the manufacturing process or by an acceptable separator from penetrating between the strands of the conductor. A 3 in. length of insulation is to be stripped from a length of the finished stranded conductor and the outer surface of the conductor is to be cleaned with a wire brush. The outer layer of the strands is to be opened and observations shall be made as to whether or not any insulation is found beneath the outer layer.