Firefighter Safety and Photovoltaic Installations Research Project

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EXECUTIVE SUMMARY

Under the United States Department of Homeland Security (DHS) Assistance to Firefighter Grant Fire Prevention and Safety Research Program, Underwriters Laboratories examined fire service concerns of photovoltaic (PV) systems. These concerns include firefighter vulnerability to electrical and casualty hazards when mitigating a fire involving photovoltaic (PV) modules systems. The need for this project is significant acknowledging the increasing use of photovoltaic systems, growing at a rate of 30% annually. As a result of greater utilization, traditional firefighter tactics for suppression, ventilation and overhaul have been complicated, leaving firefighters vulnerable to potentially unrecognized exposure. Though the electrical and fire hazards associated with electrical generation and distribution systems is well known, PV systems present unique safety considerations. A very limited body of knowledge and insufficient data exists to understand the risks to the extent that the fire service has been unable to develop safety solutions and respond in a safe manner.

This fire research project developed the empirical data that is needed to quantify the hazards associated with PV installations. This data provides the foundation to modify current or develop new firefighting practices to reduce firefighter death and injury.

A functioning PV array was constructed at Underwriters Laboratories in Northbrook, IL to serve as a test fixture. The main test array consisted of 26 PV framed modules rated 230 W each (5980 W total rated power). Multiple experiments were conducted to investigate the efficacy of power isolation techniques and the potential hazard from contact of typical firefighter tools with live electrical PV components.

Existing fire test fixtures located at the Delaware County Emergency Services Training Center were modified to construct full scale representations of roof mounted PV systems. PV arrays were mounted above Class A roofs supported by wood trusses. Two series of experiments were conducted. The first series represented a room of content fire, extending into the attic space, breaching the roof and resulting in structural collapse. Three PV technologies were subjected to this fire condition – rack mounted metal framed, glass on polymer modules, building integrated PV shingles, and a flexible laminate attached to a standing metal seam roof. A second series of experiments was conducted on the metal frame technology. These experiments represented two fire scenarios, a room of content fire venting from a window and the ignition of debris accumulation under the array.

The results of these experiments provide a technical basis for the fire service to examine their equipment, tactics, standard operating procedures and training content. Several tactical considerations were developed utilizing the data from the experiments to provide specific examples of potential electrical shock hazard from PV installations during and after a fire event.

The tactical considerations addressed include:

- Shock hazard due to the presence of water and PV power during suppression activities
- Shock hazard due to the direct contact with energized components during firefighting operations
- Emergency disconnect and disruption techniques
- Severing of conductors
- Assessment of PV power during low ambient light, artificial light and light from a fire
- Assessment of potential shock hazard from damaged PV modules and systems.

The following summarizes the findings of this research project:

1. The electric shock hazard due to application of water is dependent on voltage, water conductivity, distance and spray pattern. A slight adjustment from a solid stream toward a fog pattern (a 10 degree cone angle) reduced measured current below perception level. Salt water should not be used on live electrical equipment. A distance of 20 feet had been determined to reduce potential shock hazard from a 1000 Vdc source to a level below 2 mA considered as safe. It should be noted that pooled water or foam may become energized due to damage in the PV sytem. A summary of the distances and spray patterns which measured safe (< 2 mA) and perception (< 40 mA) currents for various PV system voltages is shown in Appendix A.

2. Outdoor weather exposure rated electrical enclosures are not resistant to water penetration by fire hose streams. A typical enclosure will collect water and present an electrical hazard.

3. Firefighter’s gloves and boots afford limited protection against electrical shock provided the insulating surface is intact and dry. They should not be considered equivalent to electrical PPE.

4. Turning off an array is not as simple as opening a disconnect switch. Depending on the individual system, there may be multiple circuits wired together to a common point such as a combiner box. All circuits supplying power to this point must be interrupted to partially de-energize the system. As long as the array is illuminated, parts of the system will remain energized. Unlike a typical electrical or gas utility, on a PV array, there is no single point of disconnect.

5. Tarps offer varying degrees of effectiveness to interrupt the generation of power from a PV array, independent of cost. Heavy, densely woven fabric and dark plastic films reduce the power from PV to near zero. As a general guide, if light

can be seen through a tarp, it should not be used. Caution should be exercised during the deployment of tarps on damaged equipment as a wet tarp may become energized and conduct hazardous current if it contacts live equipment. Also, firefighting foam should not be relied upon to block light.

6. When illuminated by artificial light sources such as fire department light trucks or an exposure fire, PV systems are capable of producing electrical power sufficient to cause a lock-on hazard.

7. Severely damaged PV arrays are capable of producing hazardous conditions ranging from perception to electrocution. Damage to the array may result in the creation of new and unexpected circuit paths. These paths may include both array components (module frame, mounting racks, conduits etc.) and building components (metal roofs, flashings and gutters). Care must be exercised during all operations, both interior and exterior. Contacting a local professional PV installation company should be considered to mitigate potential hazards.

8. Damage to modules from tools may result in both electrical and fire hazards. The hazard may occur at the point of damage or at other locations depending on the electrical path. Metal roofs present unique challenges in that the surface is conductive unlike other types such as shingle, ballasted or single ply.

9. Severing of conductors in both metal and plastic conduit results in electrical and fire hazards. Care must be exercised during ventilation and overhaul.

10. Responding personnel must stay away from the roofline in the event of modules or sections of an array sliding off the roof.

11. Fires under an array but above the roof may breach roofing materials and decking allowing fire to propagate into the attic space.

1. TABLE OF CONTENTS

1. Introduction

This research project is to address firefighter vulnerability to electrical and casualty hazards when mitigating a fire involving solar photovoltaic (PV) modules and support systems installed on structures. Total global solar energy capacity averaged 40 percent annual growth from 2000 to 2010[1]; grid-connected solar photovoltaic capacity grew 50 percent per year for much of this time[2]. This growth increases the potential of a fire department response to a building with PV, irrespective of the PV being involved with the initiation of the fire event. This growth increases the potential of a fire department response to a building with PV, irrespective of the PV being involved with the initiation of the fire event.

As a result of this increased use of PV systems in residential and commercial applications, firefighters and fire safety officials have voiced concerns about the potential risks when PV systems may be part of the fire hazard or the impact on fire department operations. Traditionally, one of the first tactics firefighters deploy when arriving at a fire scene is to secure utilities such as the electrical service, to ensure their safety during firefighting operations. This is accomplished by opening the electrical service disconnect(s) to assure that firefighters working in the structure are not exposed to electrical shock hazards. Another early tactic is to vertically ventilate the structure by cutting a hole in the roof. With the increased use of photovoltaic modules and support systems, the traditional firefighter tactics have become more complicated and created significant concerns for firefighter safety.

Firefighters often voice their concerns about the need for more information so as to develop standard operating procedures to protect against the growing hazards presented by changing technology. Regarding the increasing use of PV systems, Richard Edgeworth, Chief of Training at the Chicago Fire Department, has stated that "*the risk to my firefighters is increasing because we are seeing a significant increase in the installation of PV systems in structures and our firefighters don't have the standard operating procedures and training to address this increasing risk because we don't yet fully understand the risk.*"

Though the electrical and fire hazards associated with power generation and distribution is well known, a very limited body of knowledge and insufficient data exists to understand the fire and electrical shock risks to the fire service during a fire event involving PV systems. In addition, most of the research on the fire risks of PV systems has focused on the PV as a fire source due to internal shorting or arcing rather than implications to the fire service during their tactical response during an emergency.

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[1] International Energy Agency (IEA), Energy Technology Perspectives 2010: Scenarios and Strategies to 2050. Paris: IEA, 2010.

[2] U.S. Grid-Connected Photovoltaic Capacity Growth, 1999 – 2009. Federal Energy Regulatory Commission. June 7, 2010.

2. Objectives and Technical Plan

The object of this research project was to document firefighter vulnerability to electrical and casualty hazards when mitigating a fire involving photovoltaic modules and support systems. The project plan included a thorough review of literature to better understand the effects of electric shock on the human body, and how unsafe electric power can be transferred from live electrical equipment and components to a person's body. The research also included experiments to develop empirical data for understanding the magnitude of these hazards and unsafe conditions. Specifically, the hazards addressed included the following with respect to the presence of photovoltaic systems:

- Electrical shock during suppression activities, including presence of water and hose streams
- Electrical shock during overhaul operations, including removal of damaged PV components
- Electrical shock due to penetration of circuit paths during ventilation activities, including severing of electrical conductors and PV components
- Secondary electrical paths due to leakage current or grounding from damaged PV modules or wiring systems.
- Effectiveness of existing power disconnection and disruption techniques
- Effectiveness of alternate means to block light, including tarps and foams
- Reliability of the water tightness of PV equipment electrical boxes from suppression hose streams
- Ability of emergency personnel to assess the presence of PV power during low ambient light, including fire light truck illumination, illumination from fire, and illumination from full moon
- Effectiveness of firefighter personal protective equipment, including boots and gloves, with respect to electrical insulation properties

The results of these experiments were documented and analyzed as it pertains to the hazards and risks associated with firefighting operations. This technical report of results provides the information for educational programs such as web-based training modules that can be disseminated to fire services nationwide and used to enhance firefighter preparedness and safety. The results of this project also provide substantiation for code requirements for installation of PV systems to further enhance firefighter safety. In addition, tactical and operational guidelines and procedures may be revised by fire departments in response to the information learned from the project.

3. Project Technical Panel

A technical panel of fire service, photovoltaic, and research experts was assembled based on their previous experience with research studies, fire service practices, photovoltaic system technology and experiences, professional affiliations and dissemination to the fire service. They provided valuable input into all aspects of this project such as experimental design, PV systems, and identification of electrical shock hazard considerations. The panel made this project relevant and possible for the scientific results to be applicable to firefighters and officers of all levels. The panel consisted of:

- Sue Kateley, California Assembly Committee on Utilities and Commerce
- Vickie Sakamoto, CALFIRE
- Ken Willette, NFPA
- Bill Brooks, Brooks Engineering
- Kevin Lynn, U.S. Department of Energy
- Tim Kreis, Phoenix Fire Department
- Wes Kitchel, Santa Rosa Fire Department
- Matt Paiss, San Jose Fire Department
- Steve Bunting, Newport Beach Fire Department
- Paul Hutchinson and Don Warfield, BP Solar
- Marv Dargatz, Enphase
- Don Hughes, Senior Electrical Inspector, County of Santa Clara.
- Howard Barikmo, Sunset Technology, Inc.
- James Dalton, Coordinator of Research, Chicago Fire Department
- Terrence Moran, Public Service Electric and Gas Company

4. Previous Literature

Prior to the start of the experimentation, four topics were researched for previous literature, standards, and studies that have been conducted. These topics included research on electric shock, characterizing the human body impedance, safe touch voltages, and safe distances with water hoses from live electrical equipment.

4.1. Research on Electric Shock

Contact with electricity, whether directly with live electrical parts in normal service, or indirectly as a result of an electrical fault or other abnormal condition, could cause physical injury or even death to persons who are placed in this situation where electric current can pass through the human body. An "electric shock" can produce a range of physiological effects to the human body including perception, reaction, inability to let go, ventricular fibrillation of the heart, and electrical burns.

In the evaluation of the risks associated with direct or indirect contact with live electrical parts, certain physiological effects are critical, and these include[3]:

> **Reaction** – The body's reaction to electricity, which can be involuntary, involves muscular contractions resulting directly or indirectly from the passage of electric current through the body.
>
> **Inability to Let Go** – The body's inability to let go from electricity, often referred to as "Lock-On", is a result of tetanization of muscle tissue due to the passage of electric current through the body. If the muscles or nerves affected by the current include those that control breathing, cessation of breathing can result as long as the current flows – possibly until death by asphyxia.
>
> **Ventricular Fibrillation** -- Ventricular fibrillation is the abnormal arrhythmic contraction of the heart in a disorganized manner that is unable to pump blood. Ventricular fibrillation can be "triggered" by electric current through the heart. Once started, it is not spontaneously reversible in humans – in other words, it does not stop when the current stops. Ventricular fibrillation usually results in death to the victim unless defibrillator treatment is available within a few minutes.
>
> **Electrical Burns** – An electrical burn is necrosis of body cells caused by the thermal heating effect of electrical current through the body.

Thresholds are limits where certain effects, such as those associated with contact with electricity, begin to occur. Not all individuals in the general population have the same threshold for a given effect. For example, physical characteristics such as body weight

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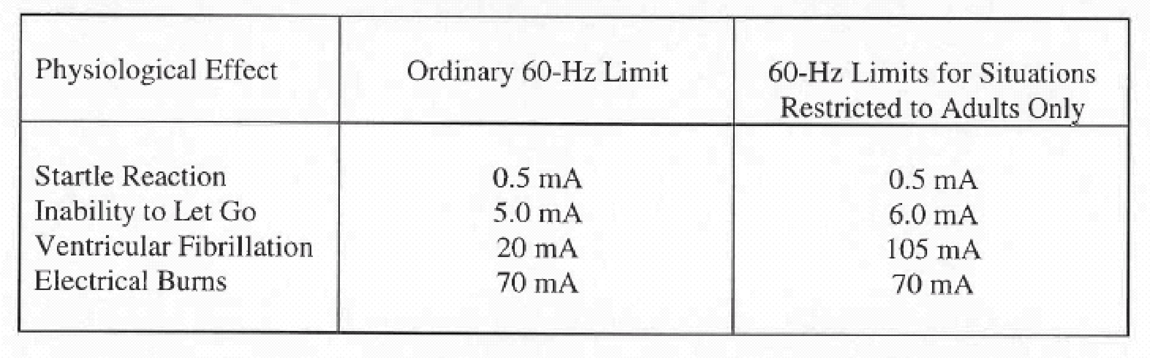
[3] "Electrical Shock," an educational presentation of Underwriters Laboratories Inc., prepared by Walter Skuggevig, 1991.

and skin sensitivity can have a direct effect on certain threshold limits, and therefore women and children tend to have lower threshold limits for electricity than most adult men. Also, the electrical characteristics of voltage and current such as frequency, wave shape, and crest factor can affect these threshold limits.

Threshold limit values for most electrical products are determined assuming that a person of any size, including children, may contact the product if a fault or other abnormal condition exists. When contact is made with a live electrical part, the current path through the body is normally hand-to-hand or hand-to-foot. Most electrical products are connected to an AC electric utility system that is operated at 50 or 60 Hz (60 Hz typical in North America). Therefore, threshold limit values for human contact with live electricity are usually expressed in terms of the physiological effect of 60 Hz current. Table 1 shows the typical ordinary 60 Hz current threshold limits for a startle reaction, the inability to let go, ventricular fibrillation, and electrical burns for the entire population and for situations restricted to adults only. [4]

Table 1. Physiological effects of 60 Hz current



Physiological Effect	Ordinary 60-Hz Limit	60-Hz Limits for Situations Restricted to Adults Only
Startle Reaction	0.5 mA	0.5 mA
Inability to Let Go	5.0 mA	6.0 mA
Ventricular Fibrillation	20 mA	105 mA
Electrical Burns	70 mA	70 mA

For installations involving direct current (DC), threshold limit values for current necessary to produce critical physiological effects are generally different than for AC. Except for thermal burns, where the limit is based on thermal heating effects and is independent of frequency, the threshold limits for DC current are generally higher than that for lower frequency alternating current (AC), especially when considering 60 Hz AC. Table 2 shows the typical ordinary DC current threshold limits for the entire population, and for situations restricted to adults only.[2]

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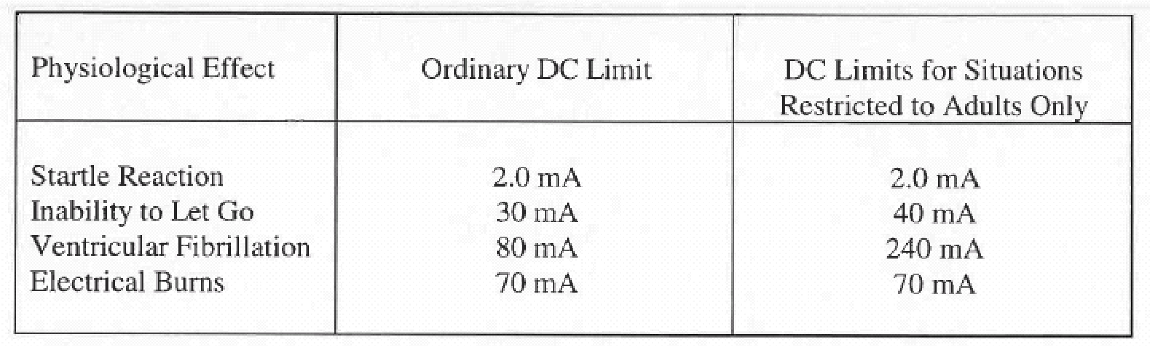
[4] Personnel Protection Devices for Specific Applications, Electric Power Research Institute, Project 6850-02, Final Report, October 1999, prepared by Underwriters Laboratories Inc.

Table 2. Physiological effects of DC current



Physiological Effect	Ordinary DC Limit	DC Limits for Situations Restricted to Adults Only
Startle Reaction	2.0 mA	2.0 mA
Inability to Let Go	30 mA	40 mA
Ventricular Fibrillation	80 mA	240 mA
Electrical Burns	70 mA	70 mA

4.2. Human Body Impedance

The electrical impedance of the human body is described in IEC Technical Specification 60479-1.[5] This document gives tables for the expected 5th, 50th, and 95th percentiles for large contact area (hand-to-hand) body impedance as a function of voltage for the adult population. Children would be expected to have somewhat higher body impedance.

A multi-component model can represent the electrical impedance of the human body. The internal body (less the skin) is represented by a resistor. This internal body resistor is in series with two parallel combinations of a resistor and capacitor. Each of these parallel combinations is intended to represent a skin surface that is in contact with a conductive surface. For DC, the total body impedance is expected to be higher than AC because the capacitive component of the skin impedance does not conduct direct current.[6]

The following Table 3 is taken from IEC 60479-1 and shows values of total body resistance (R_T) for a DC current path hand-to-hand for large surface areas of contact in dry locations.

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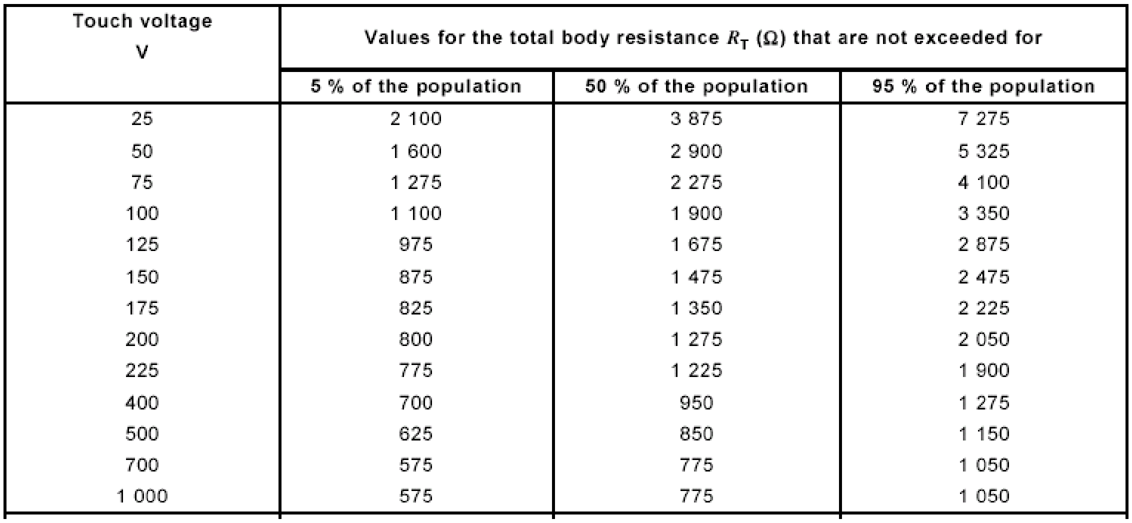
[5] IEC-60479-1, Effects of current on human beings and livestock – Part 1: General aspects, International Electrotechnical Commission, 4th ed., 2005-07.

[6] Electric Current Through the Human Body. Walter Skuggevig, Underwriters Laboratories Inc. (undated internal document).

Table 3. Total body resistance (Ohms) as a function of DC voltage

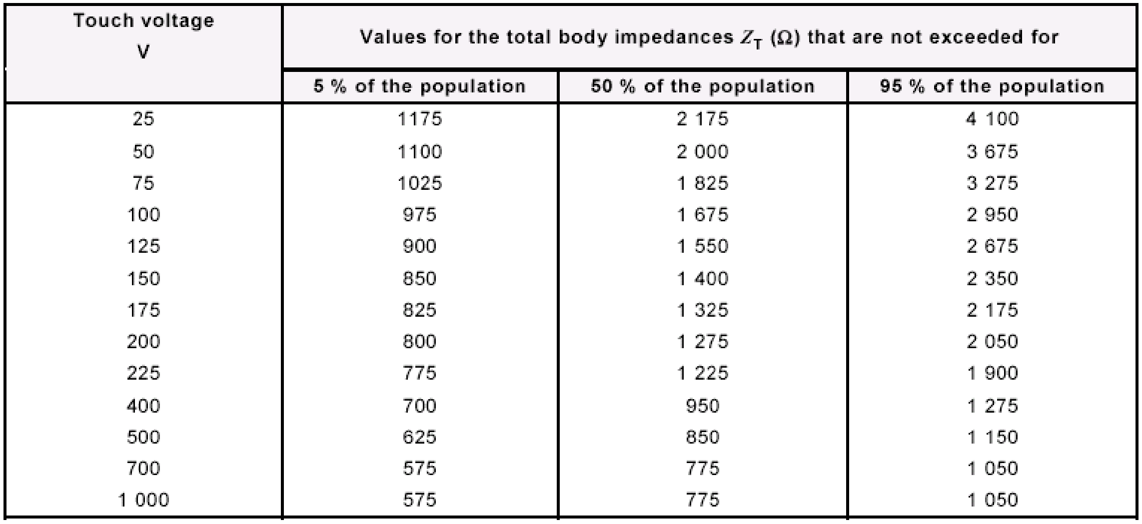


Touch voltage V	Values for the total body resistance R_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	2 100	3 875	7 275
50	1 600	2 900	5 325
75	1 275	2 275	4 100
100	1 100	1 900	3 350
125	975	1 675	2 875
150	875	1 475	2 475
175	825	1 350	2 225
200	800	1 275	2 050
225	775	1 225	1 900
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050

IEC 60479-1 explains that this data is derived from actual measurements made with DC voltages. However, the document also states that no measurements have been carried out with water-wet and saltwater-wet conditions with DC. It further states that for contact in water-wet and saltwater-wet conditions, the tables for AC can be used to represent a conservative estimate for DC conditions.

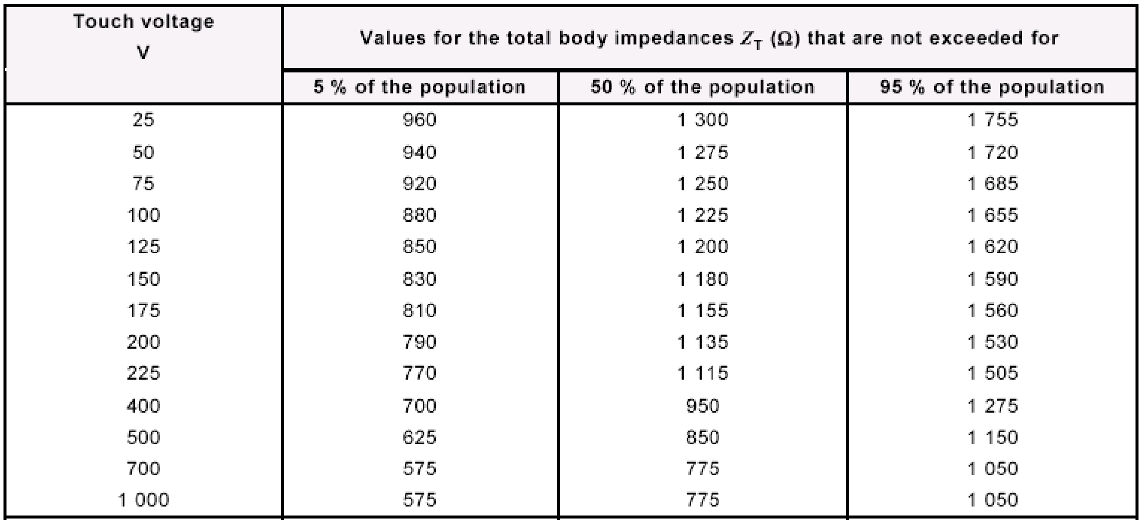
The following Table 4 and Table 5, which are taken from IEC 60479-1, show values of total body impedance (Z_T) for an AC current path hand-to-hand for large surface areas of contact in water-wet and saltwater-wet conditions respectively.

Table 4 Total body impedance (Ohms) as a function of AC voltage in water-wet conditions



Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	1175	2 175	4 100
50	1100	2 000	3 675
75	1025	1 825	3 275
100	975	1 675	2 950
125	900	1 550	2 675
150	850	1 400	2 350
175	825	1 325	2 175
200	800	1 275	2 050
225	775	1 225	1 900
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050

Table 5 Total body impedance (Ohms) as a function of AC voltage in saltwater-wet conditions



Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	960	1 300	1 755
50	940	1 275	1 720
75	920	1 250	1 685
100	880	1 225	1 655
125	850	1 200	1 620
150	830	1 180	1 590
175	810	1 155	1 560
200	790	1 135	1 530
225	770	1 115	1 505
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050

4.3. Electrical Safety Standards

The NFPA 70E® Standard for Electrical Safety in the Workplace[7] is intended to provide requirements for a safe working area for employees relative to the hazards arising from the use of electricity. Although this Standard does not specifically address hazards to firefighters from electricity, it does provide some good guidance for the practical safeguarding of employees during activities that may involve exposure to energized electrical conductors or circuit parts.

NFPA 70E requires that when any energized electrical conductors or circuit parts operating at 50 volts or more are not placed in an electrically safe work condition, then other safety-related work practices must be used to protect the employee from the electrical hazards involved. For electric shock protection, these other safety-related work practices could include maintaining a safe working distance from the exposed energized parts, using appropriate personal protective equipment (PPE) such as insulating gloves and dielectric footwear, and using insulated tools. This Standard does assume that only qualified persons, i.e. those who have skills and knowledge related to the use of electrical equipment and training to recognize the hazards involve, will be working on or near equipment that is not placed in an electrically safe work condition when at 50 volts or more.

NFPA 70E assumes that less than 50 volts is a touch potential that is considered to be "safe" from the standpoint of an electric shock hazard. Although the 2009 edition of NFPA 70E only addresses AC voltages, the 2012 edition will for the first time include requirements for DC. However, the "less than 50 volts" for not being a risk of electric shock will apply to both AC and DC circuits. In general, the human body can tolerate higher voltages (and currents) of DC than AC. This is for various reasons, including the

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[7] NFPA 70E, Standard for Electrical Safety in the Workplace, 2009 Edition, Quincy, MA., National Fire Protection Association.

fact that for constant DC, the peak voltage or current will be the DC value, but for AC, the peak of the AC sinusoidal voltage or current will be 1.4 times the AC value, which for AC is typically expressed as a root mean square (rms) value. Since many of the effects of electricity on the human body are related to the peak value of the current passing through the body, it stands to reason that the body can tolerate more DC than AC current when AC is expressed in the usual rms value.

Figure 1 provides a graph of the sinusoidal AC voltage. Figure 2 provides a graph of the constant DC voltage.

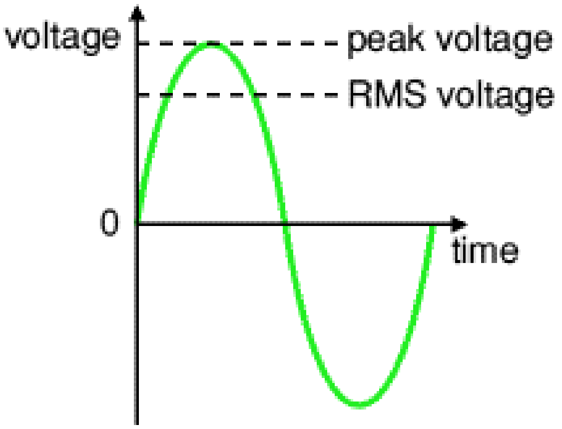

Figure 1. AC - peak voltage = 1.4 times AC RMS voltage

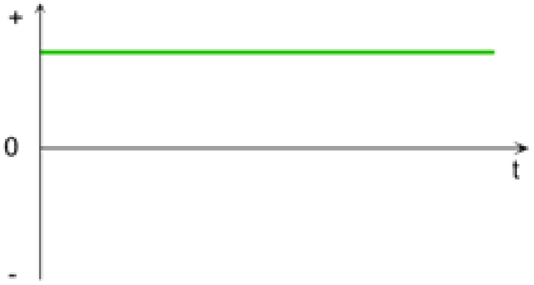

Figure 2. DC - peak voltage = DC (RMS) voltage

Other standards may describe the risk of electric shock using different values. For example, the UL 1310 Standard for Class 2 Power Units[8] (Power Supplies) describes a Class 2 source as having limited voltage and energy capacity, and a risk of electric shock is only considered to exist if continuous DC voltage exceeds 60 volts. However, for wet locations, a shock hazard is considered to exist if the DC voltage exceeds 30 volts. This is because the impedance of the body is less when wet, and thus voltage across a wet body can produce more current through the body than would be the case if the body was dry.

4.4. Safe Distances

UL requirements exist for spray hose nozzles intended for use on energized electrical equipment, however, no maximum voltages or safe distances are given for these special nozzles[9]. The National Fire Protection Association's *Fire Protection Handbook*[10] is widely referenced by the fire protection community for fire prevention practices. This *Handbook* gives limits of safe approach to live electrical equipment as reported by several different authorities. It also notes that these safe approach distances are not

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[8] UL Standard for Safety for Class 2 Power Units, UL 1310, Fifth Edition, Dated May 3, 2005, Underwriters Laboratories Inc.

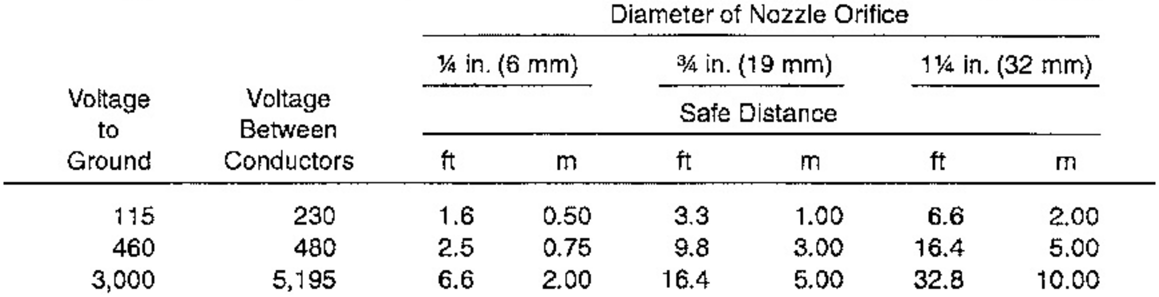
[9] Standard for Safety for Portable Spray Hose Nozzles for Fire-Protection Service, UL401. 4th ed. Underwriters Laboratories Inc.,2004.

[10] *Fire Protection Handbook*. 20th ed., Quincy, MA: National Fire Protection Association, 2008.

always consistent. It further recommends the use of water spray streams rather than solid streams, whenever possible.

The *Handbook* gives limits of safe approach to live electrical equipment based on tests made in 1958 by the Hydroelectric Power Commission of Ontario[11]. For voltages to ground of 2400 Volts, it suggests a minimum safe distance of 15 ft. for a 5/8 in. solid-stream nozzle. The *Handbook* also gives minimum safe distances between hose nozzles and live electrical equipment based on tests made in 1934 for the Fire Brigade of Paris, France. Safe distances for voltages of 3000 and less to ground are listed in Table 6 for various size nozzles.

Table 6 Minimum Safe Distances between Hose Nozzles and Live Electrical Equipment Recommended for the Paris, France Fire Brigade



		Diameter of Nozzle Orifice					
		¼ in. (6 mm)		¾ in. (19 mm)		1¼ in. (32 mm)	
		Safe Distance					
Voltage to Ground	Voltage Between Conductors	ft	m	ft	m	ft	m
115	230	1.6	0.50	3.3	1.00	6.6	2.00
460	480	2.5	0.75	9.8	3.00	16.4	5.00
3,000	5,195	6.6	2.00	16.4	5.00	32.8	10.00

The Institute of Electrical and Electronics Engineers (IEEE) Standard 979-1994, *Guide for Substation Fire Protection*[12] contains very useful information regarding electrical fires. It notes that if conditions are such that the equipment cannot be de-energized and the fire cannot be extinguished by nonconducting agents, water spray nozzles may be used as a last resort. Tests performed by several utilities substantiate that water spray nozzles can be used safely and effectively on voltages as high as 138 kV, phase-to-phase, with the following restrictions:

a) Only spray-type nozzles are used.
b) The minimum distance from the equipment is at least 10 ft (3.0 m).
c) The firefighter does not stand in a pool of water.

This standard also describes the dangers of using the wrong type of nozzle or standing too close to the energized equipment while extinguishing fires. For example, at 4000 Volts, and with a 2-1/2 in. nozzle at 100 psi and 250 gal/min solid stream, the current return to the firefighter was shown to be 7 mA (AC) at a 10 ft. distance, and 3 mA at a 20 ft. distance. However, there was zero return current at 10 ft when a 10° spray was used for the same size nozzle and water flow rate.

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[11] G.W.N. Fitzgerald, "Fire Fighting Near Live Electrical Apparatus," *Ontario Hydro Research News*, April – June 1959, vol. 11, no. 2.

[12] IEEE Guide for Substation Fire Protection Std 979-1994. The Institute of Electrical and Electronics Engineers, 1994.

In a Fire Research Technical Paper from the Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization[13], a formula is given for current flow along a solid stream of water incident to a conductor or other live part. This current will be dependent on the conductivity of the water stream and the voltage on the conductor. The current, i, is given by the following expression:

Equation 4.1 - $i = (\pi d^2/4) \bullet (cV/l)$

where V is the voltage to ground
d is the diameter of the nozzle orifice
l is the distance between the nozzle and the conductor
and c is the conductivity of the water.

4.5. Shock Hazard Due to the Direct Contact with Energized Components During Firefighting Operations

An electric shock can be produced when electric current passes through the human body. An electric shock can range from just an unpleasant experience to a more serious physiological effect that can cause injury or death. In general, the seriousness of an electric shock increases as the current increases through the body.

The amount of current that can pass through a person making direct contact with energized components is dependent upon both the amount of voltage present and the resistance in the current path. This current can be expressed by "Ohm's Law":

$$I = V / R$$

where: I equals current
V equals voltage
R equals resistance.

The resistance of a person's body can vary depending on factors such as size, weight, age, and amount of moisture. In general, a value of 500 Ohms is often used to represent a minimum value of body resistance under all of the above worst case conditions. So for example, if a person makes direct contact with a voltage source of 50 volts, and the body resistance is 500 Ohms, the electric current through the person's body would be 50 volts / 500 Ohms, which would equal 0.1 amps, or 100 milliamps.

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[13] The Shock Hazard Associated with the Extinction of Fires Involving Electrical Equipment, Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization, by M.J. O'Dogherty, Her Majesty's Stationary Office, 1965.

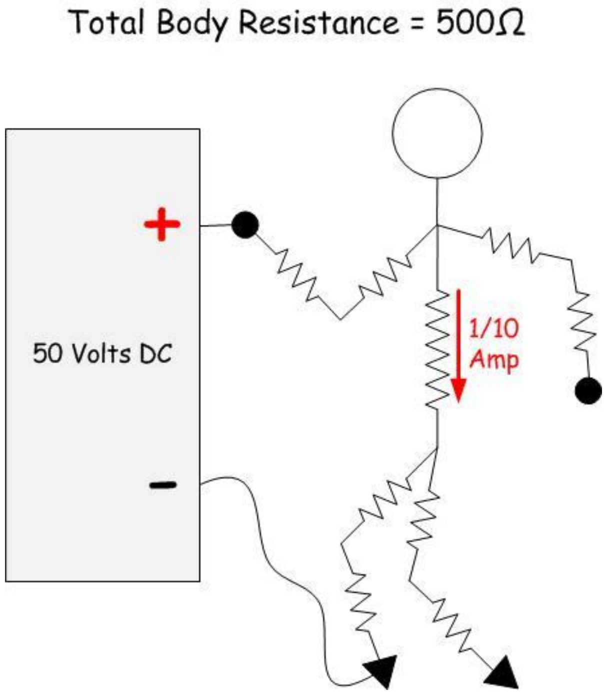

Figure 3. Electrical schematic of 500 Ohm body impedance model contacting 50 VDC hand to foot

Direct contact with energized components would usually involve a current path through the body from hand-to-hand, hand-to-foot, or foot-to-foot. Except for cases where a person might be bathing or otherwise wet with water, the resistance of the electrical circuit with the human body would much greater than 500 Ohms. This would be especially true if the person were wearing shoes or gloves, as these articles of clothing typically involve rubber, leather, or polymeric materials that are generally highly resistive in nature.

Electrical workers working on energized electrical components are required by the NFPA 70E Standard to wear special voltage rated rubber insulating gloves. These gloves are evaluated to the ASTM D 120 Standard Specification for Rubber Insulating Gloves[14]. Gloves are inspected and air tested for pinholes and other damage before each use and recertified in a laboratory every six months. Leather protectors must also be worn over the gloves in most cases to protect the rubber glove material from damage during use.

When electrical workers need additional protection from accidental contact with energized electrical components, special electric shock resistant footwear that conforms to the ASTM F 2412 Standard Test Methods for Foot Protection[15] is available. This Standard subjects the footwear to a 14,000 volt dielectric test (AC) such that the maximum permissible leakage current under dry conditions is 3 milliamps.

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[14] ASTM D120-09 Standard Specification for Rubber Insulating Gloves, ASTM International, West Conshohocken, PA.

[15] ASTM F2412 Standard Test Methods for Foot Protection, 2005, ASTM International, West Conshohocken, PA.

In the course of firefighting and overhaul operations, firefighters typically wear boots and gloves. These boots and gloves are typically tested and certified to the NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting[16]. For footwear, this Standard requires a 14,000 volt dielectric test in accordance with ASTM F 2412, which is the same requirement (3 milliamps) for the electric shock resistant footwear that some electrical workers may wear. However, the NFPA 1971 Standard has no electrical requirements for gloves.

The electrical insulation of firefighter gloves and boots could be of value when inadvertent contact with exposed energized PV system components occurs during firefighting operations. One example of inadvertent contact would be a firefighter stepping or falling on a PV module breaking the protective glass cover. Another inadvertent contact example is direct contact with a bare or cut PV wire during venting or overhaul operations. To explore the electrical insulation value of firefighter gloves and boots, leakage current experiments were conducted on new and used boots and gloves.

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[16] NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting, 2007 Edition, National Fire Protection Association, Quincy, MA.

5. PV and Firefighter Safety Experiments

Electrical and fire performance experiments were conducted to identify and quantify the electrical shock hazard that may be present to firefighters during the suppression, ventilation, and overhaul activities associated with a building or structure fire involving the presence of PV equipment. The scope of these experiments included:

- Water for Fire Suppression During Firefighting Activites with PV
- Shock Hazard Due to the Direct Contact with Energized Components
- Emergency Disconnect and Disruption Techniques
- Severing of Conductors
- Shock Hazard from Damaged PV Modules and Systems
- PV Power During Low Ambient Light, Artificial Light, and Light from a Fire
- Potential Shock Hazard from Fire Damaged PV Components and Systems

The object of this investigation was to evaluate the safety concerns to firefighters when confronted with a fire and a PV system of up to 1000 Volts DC that may not be capable of partial or complete deenergization during all stages of the firefighting and overhaul operations. The results of these experiments are intended for use in developing scientifically based firefighter training and techniques for safely and effectively combating fires with PV installations.

Representation of Results

To aid the reader in understanding the significance of the results as it pertains to the hazards of electric shock, many of the results tables in this Report include a nomenclature and color coding as follows:

- For conditions where the current through the body would be 2 mA or less, the results would be considered safe, as that is a level of DC current considered to be below the treshold of perception. In this Report, this is represented by a green highlight and/or the word "Safe."

- For conditions where the current through the body would be greater than 2 mA, but not greater than 40 mA, the results would be considered unsafe, as that is a level of DC current where it is possible for a person to percieve the presence of electricity, and this could result in a startle reaction that could result in a serious injury. In this Report, this is represented by a yellow highlight and/or the word "Perception."

- For conditions where the current through the body would be greater than 40 mA, but not greater than 240 mA, the results would be considered dangerously unsafe, as that is a level of DC current where it is possible for a person to loose muscle control and possibly lock on to the source of electricity, This could result in the cessation of breathing and asphyxiation. In this Report, this is represented by an orange highlight and/or the words "Lock On."

- For conditions where the current through the body would be greater than 240 mA the results would be considered very serious and dangerously unsafe, as that is a level of DC current where it is possible for a person’s heart to stop beating in a normal manner, and death would result if successful defibbrullation was not possible. In this Report, this is represented by a red highlight and/or the word “Electrocution.”

The following is an example of how this nomenclature is represented in this Report:

0 - 2 mA	2.1 - 40 mA	40.1 - 240 mA	> 240 MA
Safe	Perception	Lock On	Electrocution

6. Potential Shock Hazard From Water for Fire Suppression

Safe firefighting activities normally require that the building's electrical power be disconnected before water is applied to a building fire during suppression activities. This is done because the water used for fire suppression can be electrically conductive, and applying water directly to live electrical equipment could put the firefighter at risk of an electric shock. The typical electrical service to a building could involve voltages in the range of a few hundred volts AC for one- and two-family dwelling units, to several hundreds or even thousands of volts for larger commercial and industrial buildings.

Disconnecting a building's electrical power by a fire department usually involves turning off the main electrical disconnect at the building's electrical breaker panel. Any additional action such as disconnecting a service drop or removal of the building's electrical service meter may result in a dangerous arc fault or, on larger services may not result in discontinuing service. Fire departments should contact the local electrical utility to safely disconnect service.

The process of isolation from utility supplied power is inadequate for safeguarding buildings that incorporate PV systems. Turning off the PV system disconnect will de-energize the DC power on the load side of the disconnect (e.g. inverter), however, the electrical wiring and other system components between the PV modules and the disconnect can remain energized if there is sufficient light.

Although PV system equipment is designed and intended to be exposed to wet conditions, components are evaluated for resistance to water intrusion due to direct application of fire department hose streams. The following set of experiments were conducted to investigate potential shock hazard from damaged energized equipment and from direct impact from hose streams.

6.1. Experiments to Determine Safe Distances with Water Hoses from Live Electrical Equipment

Although some guidelines (Section 4.4) exist for safe approach distances for firefighters with hose streams and live electrical equipment, most of these guidelines are based on high voltages with AC power. To explore what might be a safe distance for DC power at voltages typical of a PV system, the following experiments were conducted.

6.1.1. Samples

Nozzles

Two different types of nozzles were used for these experiments, a smooth bore and an adjustable nozzle.

Smooth Bore – The smooth bore nozzle was made of aluminum with three stacked tips, 1 inch, 1-1/8 inch, and 1-1/4 inch. The nozzle(s) connected to a saber-type shutoff valve for connection to a 1-1/2 inch hose - Figure 4.

Figure 4 Smooth bore nozzle

Adjustable – The adjustable nozzle was a pistol-grip type for connection to a 1-1/2 inch hose. The nozzle was adjustable from a solid stream to a wide fog that was produced with spinning teeth – Figure 5

Figure 5 Adjustable nozzle

Water

Main Water – The main water supply for these experiments was pond water from Lake Welborn at UL's campus in Northbrook, Illinois. The water conductivity ranged from 1050 to 1125 microSiemens per centimeter (uS/cm). The local city (hydrant) water was also tested and found to be 300 uS/cm. As a result, the pond water was chosen for these experiments as its greater conductivity represented a more severe case.

Foam – A foam-water mixture was made by using a Class A foam concentrate in proportions of 0.5% and 1.0%. The 0.5% concentration had a conductivity of 1325 uS/cm, and the 1.0% concentration had a conductivity of 1525 uS/cm.

Sea Water – In some locations it may be necessary for the fire service to draw from a source of sea water or other water that may have a concentration of salt. Water with concentrations of salt can be extremely conductive when compared to other water supplies. For test purposes, a salt water solution was made using sea salt as described in the ASTM D-1141-52 Standard. The resulting solution had a salinity of 4.2% and a conductivity of 56,000 uS/cm.

6.1.2. Experiments with Pond Water

The voltage source for these tests was a DC power supply adjustable from 0 to 1000 Volts direct current (VDC). The positive (+) side of the supply was connected to a copper plate, 12 inches square, mounted in the vertical position five feet from ground on a movable skid. The negative (-) side of the supply was grounded and connected to the brass fitting connection on the hose (1-1/2 inch) at the nozzle. A 500 Ohm resistor was also included in the test circuit to represent the human body impedance[17]. The current produced in the circuit from the plate, through the hose stream, and back to the nozzle/hose fitting was then measured under various conditions of nozzle type, water pressure, and distance. Figure 6 and Figure 7 illustrate the test fixture.

Figure 6 Target plate on skid

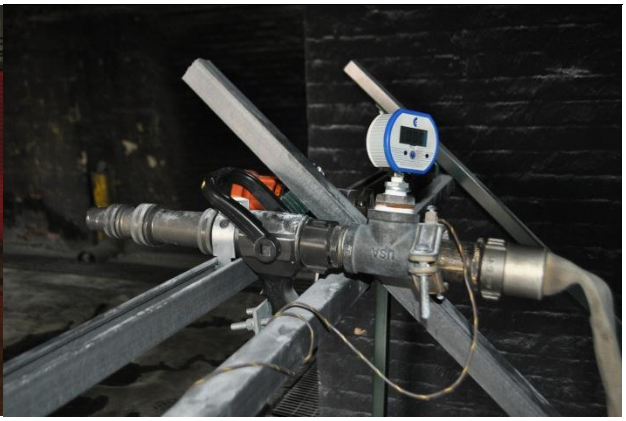

Figure 7 Electrical connection to hose fitting

Each experiment consisted of placing the target copper plate a fixed distance from the nozzle. A particular nozzle type and water pressure was then chosen. With the nozzle spray aimed at the target, the power supply was turned on at 1000 VDC. Data acquisition of voltage and current then began, and the voltage was gradually lowered from 1000 VDC to 50 VDC, dwelling for several seconds at the fixed voltages of 1000, 600, 300 and 50. Figure 8 illustrates a steady water stream aimed at the energized target plate.

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[17] See Table 3 - Total body resistance as a function of DC voltage. 500 Ohms was chosen as a minimum threshold of total body resistance from this table.

Figure 8 Water stream aimed at energized target plate

The first experiments were conducted with the smooth bore nozzles at a distance of 10 feet between the nozzle and the copper target. The water pressure was adjusted such that a constant solid stream was provided from the nozzle to the target. This resulted in water pressures of 21, 14, and 10 PSI for the 1, 1-1/8, and 1-1/4 inch diameter nozzles respectively. With the 1 inch nozzle, a higher pressure of 35 PSI was also tested.

6.1.2.1. Results

Table 7 summarizes the results of the smooth bore nozzle, solid stream at 10 foot distance experiments.

Table 7 – Results of experiments with 10 foot solid stream – smooth bore nozzle

Distance	Nozzle type/size		Pressure	Voltage	Leakage current
feet	Smooth bore	Adjustable	PSI	DC Volts	Milliamps
10	1 inch		21	1000	5.7
10	1 inch		21	600	3.2
10	1 inch		21	300	1.6
10	1 inch		21	50	0.3
10	1 inch		35	1000	4.8
10	1 inch		35	600	2.9
10	1 inch		35	300	1.4
10	1 inch		35	50	0.3
10	1-1/8 inch		14	1000	4.2
10	1-1/8 inch		14	600	2.5
10	1-1/8 inch		14	300	1.3
10	1-1/8 inch		14	50	0.2
10	1-1/4 inch		10	1000	3.5
10	1-1/4 inch		10	600	1.9
10	1-1/4 inch		10	300	0.9
10	1-1/4 inch		10	50	0.2

Similar experiments were also conducted with the adjustable nozzle with a full stream at 10 feet. As the nozzle was adjusted down from the full stream towards fog, the leakage current quickly dropped to near zero.. Table 8 summarizes the results of the adjustable nozzle, solid stream at 10 foot distance experiments

Table 8 – Results of experiments with 10 foot solid stream – adjustable nozzle

Distance	Nozzle type/size		Pressure	Voltage	Leakage current
feet	Smooth bore	Adjustable	PSI	DC Volts	Milliamps
10		solid stream	46	1000	3.4
10		solid stream	46	600	2.1
10		solid stream	46	300	1.1
10		solid stream	46	50	0.2
10		solid stream	35	1000	3.7
10		solid stream	35	600	2.1
10		solid stream	35	300	1.2
10		solid stream	35	50	0.2
10		solid stream	25	1000	2.9
10		solid stream	25	600	1.9
10		solid stream	25	300	0.9
10		solid stream	25	50	0.2

For the next set of experiments, the distance was increased to 15 feet using the 1 inch smooth bore and the adjustable nozzle at full stream. Table 9 summarizes the results of the adjustable nozzle, solid stream at 15 foot distance experiments

Table 9 – Results of experiments with 15 foot solid stream

Distance	Nozzle type/size		Pressure	Voltage	Leakage current
feet	Smooth bore	Adjustable	PSI	DC Volts	Milliamps
15	1 inch		35	1000	2.7
15	1 inch		35	600	1.8
15	1 inch		35	300	0.9
15	1 inch		35	50	0.1
15	1 inch		50	1000	2.4
15	1 inch		50	600	1.4
15	1 inch		50	300	0.7
15	1 inch		50	50	0.1
15		solid stream	46	1000	1.3
15		solid stream	46	600	1.1
15		solid stream	46	300	0.2
15		solid stream	46	50	0.1

A final set of experiments was conducted with the distance of the hose stream to the target increased to 20 feet. Using the 1 inch smooth bore nozzle and a water pressure of 23 PSI, a maximum of 1.5 mA was measured at 1000 VDC. The water pressure was then increased up to 60 PSI, and the maximum current at 1000 VDC still remained at less than 1.5 mA. A similar experiment was conducted with the 1-1/4 inch smooth bore nozzle at 29 PSI, and the maximum current at 1000 VDC remained at less than 1.5 mA. Because 1.5 mA was considered a “safe” current level, no further testing was conducted beyond 20 feet. Table 10summarizes the results of the smooth bore nozzle, solid stream at 20 feet.

Table 10 – Results of experiments with 20 foot solid stream

Distance	Nozzle type/size		Pressure	Voltage	Leakage current
feet	Smooth bore	Adjustible	PSI	DC Volts	Milliamps
20	1 inch		23	1000	1.5
20	1 inch		60	1000	1.5
20	1 1/4 inch		29	1000	1.5

For the next experiments, the distance from the nozzle to the copper target was reduced to 5 feet to represent dousing of PV components during overhaul operations. The water pressure was also reduced to provide a constant and reasonable stream to the near-by target plate. Table 11 summarizes the results of the adjustable nozzle, solid stream at 5 foot distance experiments.

Table 11 Results of experiments with 5 foot solid stream

Distance	Nozzle type/size		Pressure	Voltage	Leakage current
feet	Smooth bore	Adjustible	PSI	DC Volts	Milliamps
5	1 inch		3.4	1000	16.5
5	1 inch		3.4	600	9.9
5	1 inch		3.4	300	5.2
5	1 inch		3.4	50	0.8
5		solid stream	5.2	1000	16.9
5		solid stream	5.2	600	9.9
5		solid stream	5.2	300	5.0
5		solid stream	5.2	50	0.9

Leakage current was also evaluated for scenario representing water flow onto a horizontal target such as a roof or panel. The water pressure was reduced to provide a consistent stream to the flat target plate. The following results were found. Table 12 summarizes the results of the adjustable nozzle, solid stream at 5 foot distance to a horizontal target experiments. Figure 9 illustrates the water stream impacting the horizontal plate.

Table 12 Results of experiments with 5 foot solid stream at horizontal target

Distance	Nozzle type/size		Pressure	Voltage	Leakage current
feet	Smooth bore	Adjustible	PSI	DC Volts	Milliamps
5 (horiz)	1 inch		0.2	1000	16.7
5 (horiz)	1 inch		0.2	600	10.1
5 (horiz)	1 inch		0.2	300	5
5 (horiz)	1 inch		0.2	50	0.8
5 (horiz)	1-1/4 inch		0.3	1000	16.3
5 (horiz)	1-1/4 inch		0.3	600	9.8
5 (horiz)	1-1/4 inch		0.3	300	5.0
5 (horiz)	1-1/4 inch		0.3	50	0.8

Figure 9 Water stream aimed at flat (horizontal) energized target plate

The above test was then repeated using the adjustable nozzle with a narrow fog pattern and 1.2 PSI. No leakage current was detected for the greatest voltage of 1000 VDC.

6.1.3. Experiments with Sea Water

Testing similar to that described above was attempted using the salt water solution. However, due to the high conductivity of the salt water, which was 50 times that of the pond water, standing ground water alone was found to be sufficient for creating a high current grounding path from the live copper target plate. For safety purposes, testing with salt water was discontinued.

6.1.4. Experiments with Class A Foam

Experiments were conducted with the Class A foam in concentrations of 0.5% and 1.0%. The testing conducted used the adjustable nozzle at full stream with a pressure of 35 psi. The copper target plate was placed 10 feet from the nozzle at a horizontal orientation. For comparison purposes, the results of the similar experiments with pond water are also included. Table 13 summarizes the results of the Class A foam experiments.

6.1.4.1. Results

Table 13 Results of experiments with Class A foam

Distance feet	Voltage DC Volts	Leakage current Milliamps	Leakage current Milliamps	Leakage current Milliamps
		Pond Water (1100uS/cm)	**0.5% Foam (1325 uS/cm)**	**1.0% Foam (1525 uS/cm)**
10	1000	3.7	4.0	4.1
10	600	2.1	2.4	2.4
10	300	1.2	1.1	1.2
10	50	0.2	0.2	0.2

Because the Class A foam did not produce an appreciable difference in test results versus the previous experiments with pond water, no further testing with foam was conducted.

6.1.5. Analysis of Experiments for Safe Distances with Water Hoses from Live Electrical Equipment

When a hose stream of water is aimed at an energized electrical component, electric current can be conducted through that water stream, and subsequently conducted through the body of a person coming in contact with that hose. The amount of current present in that hose stream is dependent on several factors, including 1) the system voltage, 2) the conductivity of the water, 3) the diameter and length of the hose stream, and 4) the geometry and dispersion of the water as it travels through the air and strikes the energized component. Although the fire service has established procedures for deenergizing the utility (AC) power from a building before applying water to a fire, or maintaining a safe water stream distance from high voltage utility wires and equipment, PV systems can introduce some unique challenges to firefighters who may not be aware of or trained in addressing this specific electrical hazard.

The water used in firefighting operations is most often taken from city hydrants or drawn from a nearby body of water. Conductivity, a measure of the water’s ability to conduct electric current, is related to the types of minerals dissolved in the water and their concentration. Hence water conductivity can be expected to vary from source to source. City drinking water, typical of hydrant water, usually has a conductivity of a few hundred micro Siemens per centimeter (uS/cm). Water from a pond or lake can have a conductivity of 1000 uS/cm or more because of the additional dissolved minerals. Sea water can have a conductivity of more than 50,000 uS/cm. Because of the very high conductivity of sea water or other water sources containing salt, applying this highly conductive water to energized electrical parts would not be recommended as it could be very dangerous. Adding a firefighting foam concentrate to water will likely increase its conductivity, but not to any great extent like salt will.

Initial experiments at 1000 VDC with pond water (≈ 1100 uS/cm) and a 1-1/4 inch nozzle with a solid stream at 10 feet, produced less than 4 mA of leakage through the hose stream. The calculated maximum leakage current at these parameters is almost 30 mA[18]. The reason for this reduction in current under actual test conditions is likely due to the breakup of the solid stream over this 10 foot distance, and the dispersion of the water as it hit the target plate. These factors all created additional resistance in the water circuit, and thus resulted in less current through the water stream than expected. Figure 10 Water stream breaking up and dispersing near target plate Illustrates stream pattern impacting vertical target.

Figure 10 Water stream breaking up and dispersing near target plate

The results also seemed to show, contrary to calculations, that the 1 inch smooth bore nozzle was producing slightly more leakage current than the larger 1-1/8 and 1-1/4 inch nozzles under similar conditions. The 1 inch smooth bore nozzle at 21 PSI also produced slightly more leakage current than at 35 PSI. This all seemed to reinforce the notion that more powerful hose streams tend to breakup more and thus produce less leakage current.

The maximum leakage current measured through a 10 foot solid stream of pond water was almost 6 milliamps. A current of this magnitude could present a perception danger to the firefighter holding the hose. At 1000 volts, the leakage current through the stream did not decrease to a safe level of less than 2 milliamps until the distance was increased to 20 feet. A safe level of less than 2 millamps of current was measured with a solid stream of water at a distance of 10 feet and a potential of 300 volts.

Similar results were found with the Class A foam mixtures. At 5 feet with a narrow fog pattern, no leakage current was detected through the water even at 1000 volts.

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[18] See Equation 4.1.

6.2. Experiments with Water Aimed at PV Switch Boxes and Combiner Boxes

During structural firefighting operations electrical enclosures may be directly struck, intentionally or unintentionally, by a hose stream. In buidlings with PV systems, these electrical enclosures house PV components such as switches, overcurrent protection, and string combiners that could remain energized after inverters and disconnects are opened becase the PV modules on the input side of these devices can continue to generate power if sufficient light is present.

Electrical enclosures for use outdoors are labeled “TYPE 3R” to indicate that they are constructed to provide a degree of protection against dirt, rain, sleet, and snow. However, TYPE 3R enclosures are not evaluated for protection against directed hose streams.[19]

To evaluate the potential shock hazard posed by a direct hose stream applied to a TYPE 3R electrical outdoor enclosure to a firefighter, experiments similar to the previously described hose stream tests were conducted. For these experiments, three different TYPE 3R enclosed PV disconnect switches and three TYPE 3R enclosed PV combiner boxes were tested such that the energized target plate was replaced with an energized switch or combiner box. The following switches and combiner boxes were tested.

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[19] UL Standard for Safety for Enclosures for Electrical Equipment, Environmental Considerations, UL 50E First Edition, Dated September 4, 2007.

6.2.1. Samples

Switch S1 – Disconnect switch rated 30 A, 250 VDC, Type 3R. Enclosure size 11 x 6-1/2 x 5-1/2 inches deep. Provided with a hinged door with no gasket. Figure 11 and Figure 12

Figure 11 Switch S1

Figure 12 Switch S1 Open

Switch S2 – Disconnect switch rated 30 A, 600 VDC, Type 3R. Enclosure size 14 x 6 x 4 inches deep. Provided with a hinged door with no gasket. Figure 13 and Figure 14

Figure 13 Switch S2

Figure 14 Switch S2 Open

Switch S3 – Disconnect switch rated 30 A, 600 VDC, Type 3R. Enclosure size 16 x 8 x 51/2 inches deep. Provided with a hinged door with no gasket.

Figure 15 and Figure 16

Figure 15 Switch S3

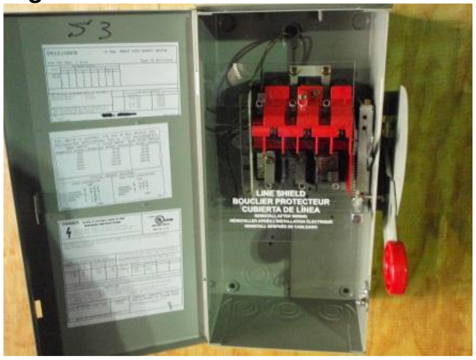
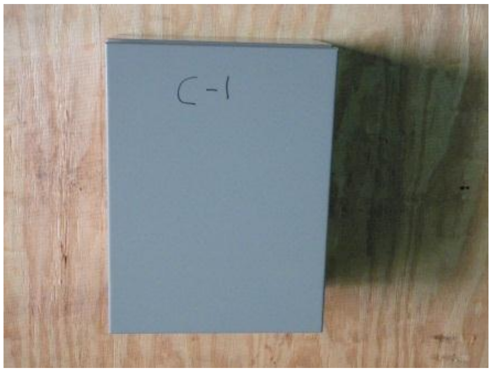


Figure 16 Switch S3 Open



Combiner Box C1 – Combiner Box rated 30 A, 600 VDC, Type 3R. Enclosure size 16 x 12 x 7-1/2 inches deep. Provided with hinged door and gasket.   Figure 17 and Figure 18

Figure 17 Combiner Box C1

Figure 18 Conbiner Box C1 Open

Combiner Box C2 – Combiner Box rated 120 A, 600 VDC, Type 3R. Enclosure size 13 x 8 x 3-1/2 inches deep. Provided with telescoping door with no gasket.
Figure 19 and Figure 20

Figure 19 Combiner Box C2

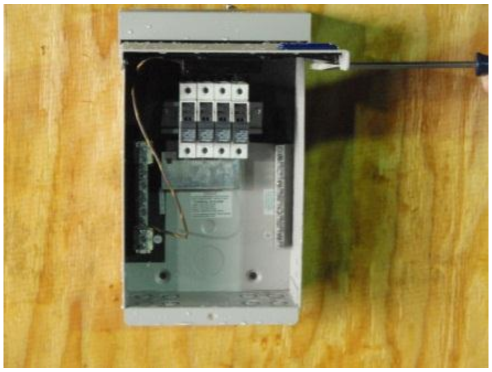


Figure 20 Combiner Box C2 Open

Figure 21 Combiner Box C3

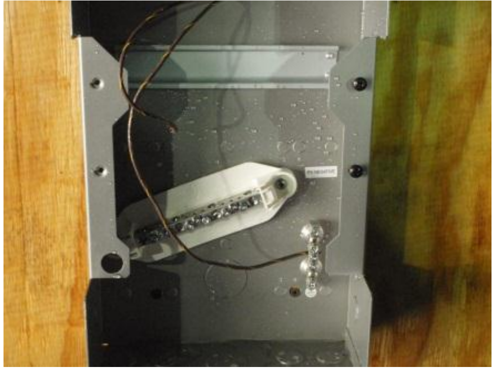


Figure 22 Conbiner Box C3 Open

Combiner Box C3 – Combiner Box rated 120 A, 600 VDC, Type 3R. Enclosure size 14 x 9 x 4 inches deep. Provided with telescoping door with no gasket. Figure 21 and Figure 22

6.2.2. Experimental Method

For these experiments, the enclosure was mounted vertical on a plywood surface. No conduit fittings were used and none of the box knock-outs were removed. All of the poles of the switch or combiner were connected to the positive (+) side of a DC power supply. The metal enclosure was connected to the negative (-) side of the DC power supply. The leakage current in the circuit was measured with a DC ammeter.

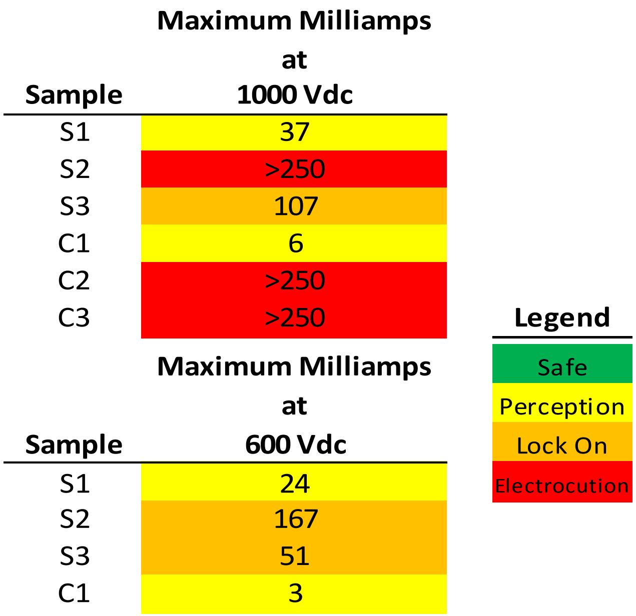
With the DC power supply energized at 1000 VDC, a water stream (pond water) was applied from a distance of 20 feet using a 1 inch smooth bore nozzle at a pressure of 25 PSI. No external resistance to represent the body impedance was used in the test circuit for the tests. The water stream was applied for 2-1/2 minutes, and the maximum leakage current in the circuit during the test was recorded. Upon completion of the test, the enclosure door was opened and the enclosure was inspected for entrance of water.

The experiments were repeated on samples S1, S2, S3, and C1 at 600 VDC, and with a 500 Ohm resistor in the test circuit to represent the body impedance.

6.2.3. Results

The results of the tests at 1000 VDC are shown below. Water flowing from inside of Samples C2 and C3 was observed almost immediately after starting the test. When the enclosure doors were opened at the conclusion of the test, water was observed on the live parts of all the enclosure samples. Only water droplets were observed inside sample C1. Table 14 Results of experiments with switch and combiner boxessummarizes the current levels measured at 1000 and 600 volts DC.

Table 14 Results of experiments with switch and combiner boxes



Sample	Maximum Milliamps at 1000 Vdc
S1	37
S2	>250
S3	107
C1	6
C2	>250
C3	>250

Sample	Maximum Milliamps at 600 Vdc
S1	24
S2	167
S3	51
C1	3

Legend
Safe
Perception
Lock On
Electrocution

Table 5.1.8.1 –

6.2.4. Analysis of Experiments with Water Aimed at PV Switch Boxes and Combiner Boxes

PV systems often include outdoor electrical enclosures for disconnect switches, over current protection, and combiner boxes. During a fire, some firefighting tactics may involve the intentional or unintentional aiming of water at these electrical enclosures. Components in these enclosures may remain energized even after inverters and disconnects are opened because the PV modules on the input side of these enclosures will continue to generate power if sufficient light is present.

Electrical enclosures for use outdoors (TYPE 3R) are only tested to provide a degree of protection against dirt, rain, sleet, and snow. They are not evaluated for water penetration resistance to direct hose stream impact.

Direct hose stream experiments conducted on six Type 3R outdoor PV component electrical enclosures demonstrated that direct hose stream contact can cause water penetration into the enclosure energizing the metal enclosure. This could present a severe shock and possibly even an electrocution hazard to a firefighter in contact with the metal enclosure both during the application of water and when the hose line is shutdown if polling has occurred in the box.

7. Electrical insulating properties of firefighter gloves and boots

Safe firefighting activities require personal protective equipment (PPE) designed specific for the hazards encountered during those activities and include helmets, turnout gear, boots and gloves. These equipment provide a level protection from abrasion, impact and thermal energy.

Electrical workers working on energized electrical components are required by the NFPA 70E Standard to wear special voltage rated rubber insulating gloves. These gloves are evaluated to the ASTM D 120 Standard Specification for Rubber Insulating Gloves . Gloves are inspected and air tested for pinholes and other damage before each use and recertified in a laboratory every six months. Leather protectors must also be worn over the gloves in most cases to protect the rubber glove material from damage during use.

When electrical workers need additional protection from accidental contact with energized electrical components, special electric shock resistant footwear that conforms to the ASTM F 2412 Standard Test Methods for Foot Protection is available. This Standard subjects the footwear to a 14,000 volt dielectric test (AC) such that the maximum permissible leakage current under dry conditions is 3 milliamps .

In the course of firefighting and overhaul operations, firefighters typically wear boots and gloves. These boots and gloves are typically tested and certified to the NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting . For footwear, this Standard requires a 14,000 volt dielectric test in accordance with ASTM F 2412, which is the same requirement (3 milliamps) for the electric shock resistant footwear that some electrical workers may wear. However, the NFPA 1971 Standard has no electrical requirements for gloves.

The electrical insulation of firefighter gloves and boots could be of value when inadvertent contact with exposed energized PV system components occurs during firefighting operations. One example of inadvertent contact would be a firefighter stepping or falling on a PV module breaking the protective glass cover. Another inadvertent contact example is direct contact with a bare or cut PV wire during venting or overhaul operations. To explore the electrical insulation value of firefighter gloves and boots, leakage current experiments were conducted on new and used boots and gloves.

7.1. Experiments to Determine Electrical Properties

Although typical fire fighters PPE are manufactured from nonconductive materials, fire fighting operations exposes the gear to electrically conductive containminents such as water and soot. To explore what protection standard gear may provide, experiments were conducted on gloves and boots in new, wetted, soiled and damaged conditions.

7.2. Samples – Gloves and Boots

Three common types of gloves used by firefighters were selected for electrical insulation testing. Descriptions of the procured gloves as listed {in the catalog} are as follows:

Glove #1 – Described in a supplier’s catalog as a supple all-leather, lightweight construction leather glove to provide basic fire protection. Offers a roomy Gunn cut design with wing thumb, seamless index finger for extra durability, full sock-type liner of comfortable flame resistant SEF material, and a 2" leather cuff. These gloves are claimed to meet FED, CAL-OSHA specifications, but do not meet NFPA standards. Cost $33.95. Figure 23

Figure 23 Glove 1

Glove #2 - Described in a supplier’s catalog as offering unmatched comfort, protection and performance in an NFPA fire glove. Waterproof, breathable barrier system that is the same proven technology used by many of the leading turnout gear manufacturers. Every liner is sewn, seam sealed and 100% dunk tested. Technology designed for better dexterity, no liner pull-outs and performance even after exposures in hot structural environments. Heavy weight tanned outer shell claimed to remain soft after repeated soakings. Cost $47.95. Figure 24

Figure 24 Glove 2

Glove #3 - Described in a supplier’s catalog as true 3-D hand-shaped styling with staggered layer seaming, and construction with dead air spacer ridges to allow natural hand flexing. Black cowhide cuffs with top grain kangaroo leather on back for easy flex and durability. High temperature stable and durable moisture barrier and wool 3-D heat guard on the back of hand to deliver extra insulation and thermal lining architecture that preserves microcapsules of air for thermal protection without traditional bulk. UL Classified to NFPA 1971, 2007 edition. Cost $133.95. Figure 25

Figure 25 Glove 3

Three common types of boots used by firefighters were selected for electrical insulation testing. Descriptions of the procured boots as listed {in the catalog} are as follows:

Boot #1 - Described as a fire-grade rubber boot formulated for high-heat stability, watertightness and resistance to contaminant deterioration. Provided with an extra-dense lining of heavy duty wool felt plus a polyfoam insulation covering the entire foot and shaft. Offers protection with built-in steel toe cap, bumper guards, tempered steel shanks and stainless steel midsoles. Boots have a durable outsole that provides protection and stability. Claimed to exceed NFPA standards, and meets all ANSI, OSHA & CAL-OSHA standards. UL Classified to NFPA 1971, 2007 edition. Cost $143.95. Figure 26

Figure 26 Boot 1

Boot #2 - Described as designed to be up to 25% lighter than heavier conventional fireboots. Incorporates innovative latex rubber dipping process that eliminates seams and produces lighter weight boots. High abrasion resistant outsole and heel with built-in shin guard and foot-guard protection system. UL Classified to NFPA 1971, 2007 edition. Cost $153.95. Figure 27

Figure 27 Boot 2

Boot #3 - Described as waterproof, flame and cut-resistant leather upper. Polyurethane insole with removable insert, plus rubber midsole and steel shank with built-in shin guard and steel toe. Waterproof and blood borne pathogen resisting lining. Claimed to meet ASTM F2413-05. UL Classified to NFPA 1971, 2007 edition. Cost $239.95. Figure 28

Figure 28 Boot 3

7.2.1. Experiments with New Gloves

The following procedures were used to test new gloves for their electrical insulation value with voltages up to 1000 volts DC:

1) The glove was filled with metal shot to 2 inches below cuff line.

2) A non-conductive container was filled with metal shot sufficient to immerse the glove to 3 inches below cuff line.

3) Electrodes in the container shot and the glove shot were connected to the positive and negative sides of a 0 - 1000 VDC variable power supply and a 500 Ohm resistor was placed in the circuit to represent human body impedance.

4) Leakage current in the circuit was measured with an ammeter at 50, 300, 600, and 1000 VDC.

Figure 29 illustrates the dry glove test configuration.

Figure 29 Testing a glove in metal shot

7.2.2. Experiments with New Gloves Wetted

Electrical insulation of wet, new gloves was evaluated using the same test methodology described for dry, new gloves with the exception of the following methodology for wetting the gloves:

1) The outside of the glove was saturated in tap water[20] and wrung dry.

2) The test for new gloves, steps 1 – 4 above, was repeated.

3) The outside and inside of the glove was saturated in tap water and wrung dry.

4) The test for new gloves, steps 1 – 4 above, was repeated.

Figure 30 illustrates the wet glove test configuration.

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[20] The tap water for these experiments had a conductivity of 332 uS/cm.

Figure 30 Wetting a glove before test

7.2.3. Experiments with Simulated Used Gloves

Salt and soot contamination simulating perspiration and overhaul use were simulated in the new gloves by the following process:

1) The glove was soaked for 14 hours in a salt water solution with conductivity of 11,000 uS/cm   A review of literature showed that human sweat has a conductivity of 2000 - 11000 uS/cm[21].

2) The glove was removed from the salt water, wrung dry, and then place in an air circulating oven at 60 ^{o}C until completely dry.

3) Burnt wood char was applied to the outside of the glove sufficient to soil at least 75% of glove surface area.

4) The inside of the glove was atomized with a salt water solution of 11,000 uS/cm to represent human sweat, and the test for new gloves, steps 1 – 4 above, was repeated.

5) The outside of the glove was saturated in tap water and wrung dry.

6) The test for new gloves, steps 1 – 4 above, was repeated.

7) The outside and inside of the glove was saturated in tap water and wrung dry.

8) The test for new gloves, steps 1 – 4 above, was repeated.

Figure 31, Figure 32 and Figure 33 illustrate gloves 1, 2 and 3 as soiled specimens.

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[21] T. S. Licht, M. Stern and H. Shwachman, "Measurement of the Electrical Conductivity of Sweat", Department of Chemistry, Boston College publication, June 8, 1956.


Figure 31 Glove #1 soiled


Figure 32 Glove #2 soiled


Figure 33 Glove #3 soiled

7.2.4. Experimental Method with New Boots

1) The boot was filled with tap water 6 inches from bottom of boot.

2) A non-conductive container was filled with tap water sufficient to immerse the boot 6 inches.

3) Electrodes were installed in the container water and the boot water, and a DC power supply, variable 0 - 1000 volts, was connected “plus” and “minus” to each electrode.

4) A 500 Ohm resistor was placed in the circuit to represent the body impedance, and at DC voltages of 50, 300, 600, and 1000 volts, the DC leakage current in circuit was measured with an ammeter.

7.2.5. Experimental Method with Simulated Used and Damaged Boots

1) At the thinnest toe area of the boot (over the toe plate), 50% of the material thickness was removed in a small section.

2) The test for new boots, steps 1 – 4 above, was repeated, except that the water to fill the boot was a salt water solution of 11,000 uS/cm to represent human sweat.

3) At the thinnest toe area of the boot (over the toe plate), the remaining material in a small section was removed to expose the toe cap.

4) The test in step 2 was repeated.

5) A 3/8 inch hole was drilled into the bottom of the sole of boot up to and to expose the steel sole plate or shank.

6) The test in step 2 was repeated.

Figure 34 illustrates the boot experiment configuration.

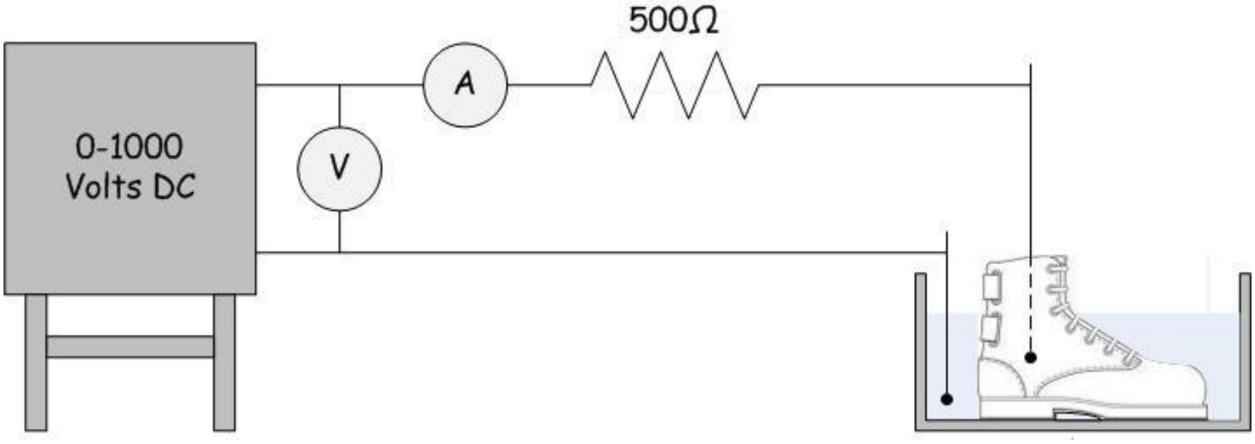

Figure 34 Diagram of boot test set-up

Figure 35 **and** Figure 36 **illustrate material removed from boot #1.**

Figure 35 Boot #1 with material removed

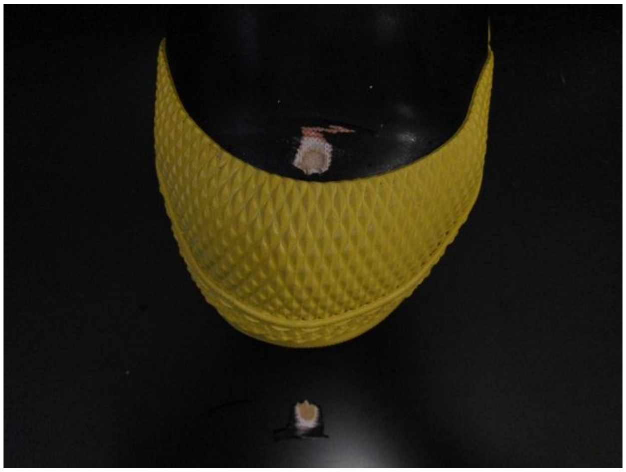

Figure 36 Boot #2 with material removed

Figure 37 illustrates material removed from boot #2 exposing the steel toe plate. Figure 38 illustrates material removed exposing the steel shank of boot 2.

Figure 37 Boot #3 with material removed

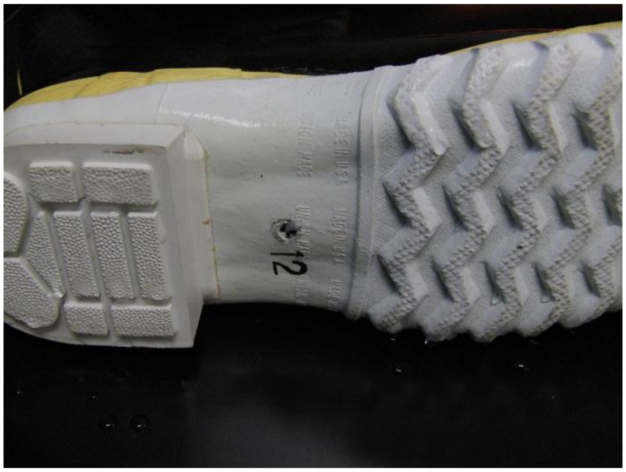

Figure 38 Puncture hole in bottom of Boot

7.3. Results

The results of the experiments with firefighter's boots and gloves are included in Table 15 and Table 16 below. A leakage current in the circuit of less than 2 milliamps would represent a safe condition, as at that level there should be no perception of electric current through the human body. Leakage currents of 2 milliamps or greater, but less than 40 milliamps, could be a concern, as a firefighter might perceive body current and react to this electric shock in a manner that could cause a sudden movement and potential fall injury. Leakage currents of 40 milliamps or greater, but less than 240 milliamps, could be a danger in that the body's muscle tissue may tetanize (lock-on) and lose the ability to let-go, which can also lead to loss of breathing control. Leakage currents of 240 milliamps and greater can be of extreme danger and electrocution death is possible from sudden heart fibrillation.

Gloves

Table 15 Results of experiments with gloves

Glove Sample	Soiled	Wetted Outside	Wetted Inside	Measured milliAmps, DC 50 Vdc	300 Vdc	600 Vdc	1000 Vdc
1	no	no	no	🟩	🟩	🟩	0
2	no	no	no	🟩	🟩	🟩	0
3	no	no	no	🟩	🟩	🟩	0
1	no	yes	no	91	>250	🟥	🟥
2	no	yes	no	0.5	2	100	>250
2	no	yes	yes	38	89	>250	>250
3	no	yes	no	3	17	24	54
3	no	yes	yes	43	>250	🟥	🟥
1	yes	no	no	🟩	🟩	🟩	0.5
2	yes	no	no	🟩	🟩	🟩	0
3	yes	no	no	🟩	🟩	🟩	0
1	yes	yes	no	91	>250	🟥	🟥
1	yes	yes	yes	93	>250	🟥	🟥
2	yes	yes	no	0	2	3	4
2	yes	yes	yes	64	>250	🟥	🟥
3	yes	yes	no	0	0	0	0
3	yes	yes	yes	78	>250	🟥	🟥

🟩 Safe	🟨 Perception	🟧 Lock On	🟥 Electrocution

Boots

Table 16 Results of experiments with boots

Boot		50% Toe	100% Toe	Hole in	Measured milliAmps, DC[4]			
Sample	New	Aged[1]	Aged[2]	Bottom[3]	50 Vdc	300 Vdc	600 Vdc	1000 Vdc
1	X				🟩	🟩	🟩	0
2	X				🟩	🟩	🟩	0
3	X				6	45	94	160
1		X			1	7	18	35
2		X			13	108	>250	🟥
3		X			13	99	>250	🟥
1			X		4	78	135	240
2			X		30	184	>250	🟥
3			X		26	>250	🟥	🟥
1				X	27	178	>250	🟥
2				X	31	212	>250	🟥
3				X	30	204	>250	🟥

🟩 Safe 🟨 Perception 🟧 Lock On 🟥 Electrocution

[1] - At the thinnest toe area, 50% of the material thickness removed.

[2] - At the thinnest toe area, 100% of the material thickness removed.

[3] - 3/8 inch hole drilled in sole to expose steel sole plate.

[4] - 500 Ohm resistor included in circuit to represent body impedance.

7.4. Analysis

Under certain conditions firefighter’s boots and gloves can provide some good electrical insulation and protect the body against electric shock, even up to 1000 volts DC.

Firefighter’s gloves are not tested for electrical insulation; however the samples of leather gloves tested here were found to provide good electrical insulation, even up to 1000 volts, when new and even when soiled, provided they were dry. As the leather gloves became wet, even those with moisture barriers provided little or no protection against a dangerous electric shock in most cases. The special rubber insulating gloves worn by electrical workers when working on energized electrical components are routinely tested for their electrical insulation and material integrity properties, as even pinholes in the gloves can be dangerous when contacting high voltage live parts. Firefighter’s gloves should never be considered a substitute for voltage rated insulating gloves if it is known that energized electrical components may be contacted.

Firefighter’s boots that are certified to the NFPA 1971 Standard are tested new up to 14,000 volts, which is well beyond the voltages typically encountered in PV systems. However, this NFPA 1971 boot test is conducted in a dry environment, and non-rubber (leather) boots that were tested here were found to provide poor electrical insulation when wet. Firefighter’s boots typically incorporate conductive metal toe plates and sole plates for crush and puncture protection, and if old or damaged boots compromise the integrity of the outer boot material (e.g. wear away rubber or leather), this could expose the person wearing the boot to a possible shock hazard if energized components are contacted.

8. PV Test Array

For testing purposes, a temporary structure and PV test array was built at the UL facility property located in Northbrook, Illinois. The structure upon which the array was mounted consisted of an approximate [28 x 48 ft] wood building (wooden truss design) with a single-sided roof surface 48 ft long and 32 ft wide at a 7:12 slope. The roof was sheathed with 5/8 in O.S.B. and covered with 15 lb felt paper and Class A gray asphalt shingles. The roof surface was faced in a south direction. Figure 39illustrates the roof for the PV array under construction.

Figure 39 Construction of temporary PV test structure

The main test array consisted of 26 PV framed modules rated 230 W each (5980 W total rated power). Each module was rated 37.08 V open circuit (Voc), 8.11 A short-circuit current (Isc). At maximum power, the rated voltage is 20.45 V (Vmp), and rated current is 7.55 A (Imp). Each module measured 1652 mm by 992 mm, with a depth of 50 mm and weight of 23.5 kg. Each module contained 60 multicrystalline silicon cells in a 10 x 6 matrix series connected. The construction included three by-pass diodes, and a front tempered glass 3.2 mm thick.

Figure 40 illustrates the PV test array installed on the roof.

Figure 40 Main test array with 26 PV modules

With all 26 framed modules wired in series, the maximum open-circuit voltage was 964 V, and at maximum power the voltage would be 792 V. The roof structure also included an open test bed area, approximately 19 ft wide adjacent to the main array, where additional modules and/or different PV technology devices could be mounted and wired to the main array for test purposes.

A second PV technology consisted of PV laminate modules mounted to metal pans (18 inches on center) typical of a standing seam metal roof construction. Each laminate was rated 68 W (P_{max}), 23.1 V open circuit (V_{oc}), 5.1 A short-circuit current (I_{sc}). At maximum power, the rated voltage is 16.5 V (V_{mp}), and rated current is 4.13 A (I_{mp}). Each laminate measured 2849 mm by 394 mm, with a depth of 4 mm and weight of 3.9 kg. Each laminate contained 11 amorphous silicon cells connected in series, with a by-pass diode connected across each cell.

Figure 41 illustrates the PV array with test specimens installed on the right.

Figure 41 Complete structure with PV framed modules and laminates

9. Emergency Disconnect and Disruption Techniques

Article 690 of the National Electrical Code® (NEC®) requires PV systems to be provided with a means to disconnect all current-carrying DC conductors of a PV system from all other conductors in the building or structure. This disconnecting means must be located at a readily accessible location on the outside of the building, or inside nearest the point of entrance of the system conductors. The disconnecting means must also be marked to identify it as a PV system disconnect. In addition to disconnecting the PV DC conductors, a means must also be provided to disconnect equipment, such as inverters and charge controllers from all ungrounded conductors. Figure 42 illustrates a typical PV component configuration.

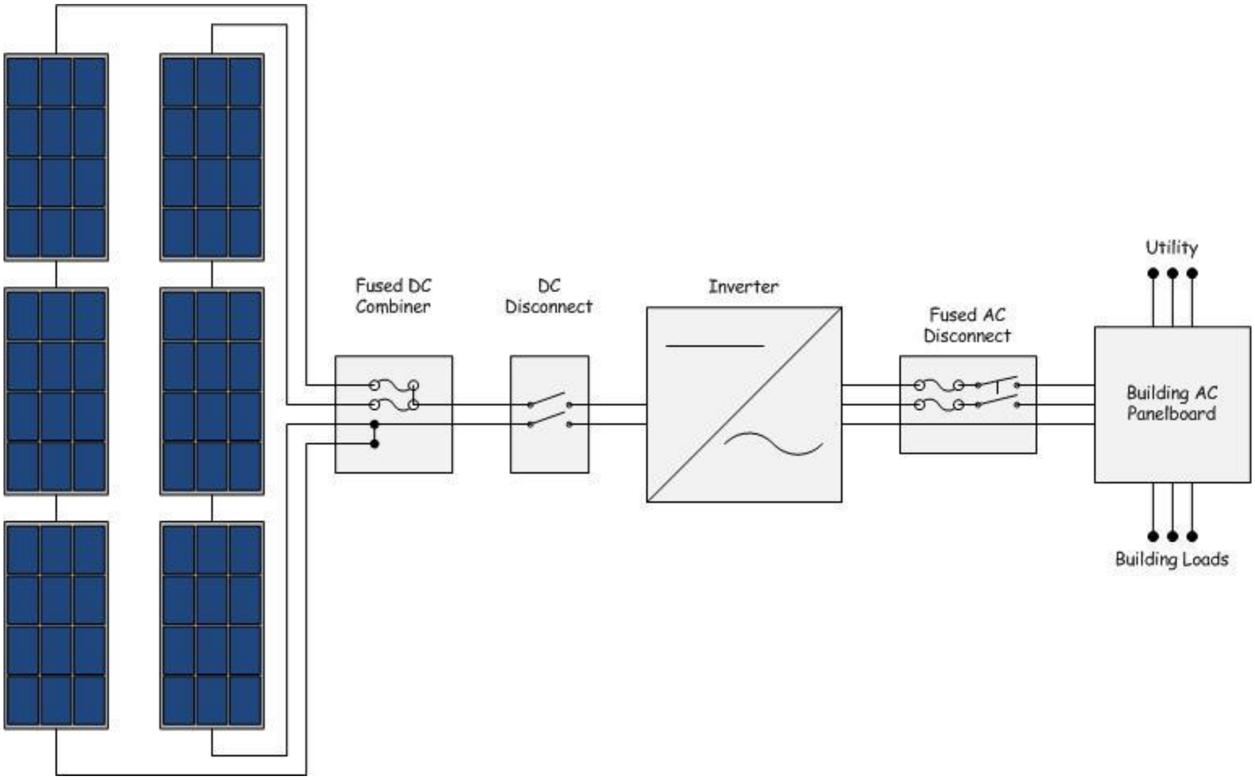

Figure 42 Diagram of typical PV system with required disconnects

However, when the required PV system disconnect is opened, the conductors between the PV modules and the disconnect can, and most often will, remain energized, especially during daylight hours when PV modules within the array are producing power. This can present an electric shock hazard to firefighters and others who may come in direct contact with energized wires and components, including PV modules themselves, on the line side of the disconnect.

PV modules consist of solar cells that generate DC electricity when exposed to light. Since sunlight is the main source of light for PV systems, it is important to know the total amount of sunlight, or solar irradiance, that the sun is producing at any given time to know the amount of power that a PV system is producing. Solar irradiance, or radiation from the sun, is measured as power density in Watts per square meter (W/m^2), This solar radiation reaching the earth can vary depending on several factors, including as time-of-day, time-of-year, atmospheric conditions such as clouds, haze, rain, etc., as well as geographical location. The maximum solar radiation reaching the earth can approach 1400 W/m^2, however, 1000 – 1200 W/m^2 is more typical of maximum irradiance on a sunny day in many parts of the United States, and even much less on cloudy or overcast days[22].

PV modules are typically rated under what is referred to as standard test conditions or STC for short. These standard test conditions are solar irradiance of 1000 W/m^2 and air temperature of 25 ^{o}C. With increases or decreases in solar irradiance, the power being generated by the PV module will also increase or decrease proportionally to a certain extent. Air temperature can also affect the power output of a PV module, and especially the output voltage. As temperature increases, the PV module output voltage will decrease because of the higher cell resistance. Conversely, lower temperatures can increase the voltage. Therefore, a PV module rated 230 W, with rated voltage at maximum power (Vmp) being 30.45 volts, and rated current at maximum power (Imp) being 7.55 amps, will only have these characteristics at a solar irradiance of 1000 W/m^2 and at a temperature of 25 ^{o}C.

9.1. Experiments for Emergency Tactics to Block Illumination

During firefighting operations, the best a firefighter can often do to deenergize parts of a PV system would be to open all PV disconnecting means, realizing that the conductors and components between the PV modules and the disconnect will likely still remain energized. Other tactics must be used to avoid contact and prevent an electric shock from these conductors and components, as they will remain energized as long as there is illumination.

During other operations such as overhaul, it may be necessary to block illumination of the PV module in order to provide a safe work environment. Some techniques to block illumination could include tarps to cover the modules in the array, or the application of foam to block the light. There have been some reports of attempting to use foam to block illumination from the sun as a means of providing a safe work environment with PV[23]. The following experiments were conducted to evaluate the effectiveness of various tarps and foam to block illumination and reduce the electric shock hazard.

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[22] *Monitoring Solar Radiation and Its Transmission through the Atmosphere,* David R. Brooks, Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA.

[23] http://www.febbex.com/pdfs/Flyer%20dark%20night%2013%2005%202009-engl.pdf, last access date 17/05/2011.

9.1.1. Samples - Tarps

Four different types of tarps were chosen for these experiments as follows:

Tarp #1 –10 x 25 foot black plastic film sheet, 4 mils thick. Cost $15.

Tarp #2– 12 x 16 foot all-purpose tarp, 5.1 mil thick, blue in color. Cost $16.

Tarp #3 – Canvas fire salvage tarp, green in color. Claimed to meet NFPA 701[24]. Cost $78.

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[24] *NFPA 701: Standard Methods of Fire Tests for Flame Propagation of Textiles and Films,* Quincy, MA: National Fire Protection Association, 2010.

Tarp #4 – 12 x 14 foot heavy vinyl fire salvage tarp, red in color. Claimed to meet ASTM E-84[25] and UL 214[26]. Cost $94.

9.1.2. Experimental Method

Weather conditions at the time of these experiments were sunny, with a solar irradiance of 1000 – 1100 W/m^2, and a temperature of 24 ^{o}C. Four framed modules in series were used for these tests. Each module was rated 230 watts, with 37.08 V open circuit (Voc), 8.11 A short-circuit current (Isc). At standard test conditions, the output of the four-module array would be approximately 148 volts open circuit, and 8 amps short circuit.

Each tarp was unfolded and spread across the entire four-module array with a single layer. The open circuit voltage of the array was then measured, followed by a measurement of the short circuit current.

9.1.3. Results

The results of the tests with tarps to block illumination are included in the following Table 17.

Table 17 Results of experiments with tarps

Tarp #	Cost	Tarp	Color	Layers	Open Circuit Volts	Short Circuit Amps	Hazard
1	$15	4.0 mil plastic film	Black	1	33	0	Safe
2	$16	5.1 mil all purpose plastic	Blue	1	126	2.1	Electrocution
3	$78	Fire Salvage Canvas	Green	1	3.2	0	Safe
4	$94	Fire Salvage Heavy Vinyl	Red	1	124	1.8	Electrocution
		Full Sun			148	8.1	

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[25] ASTM E84 - 11a Standard Test Method for Surface Burning Characteristics of Building Materials, ASTM International, West Conshohocken, PA.

[26] UL Standard for Safety for Test for Flame-Propagation of Fabrics and Films, Underwriters Laboratories Inc. WITHDRAWN.

9.1.4. Samples - Foam

9.1.5. Experimental Methods - Foam

For this experiment, a Class A foam concentrate used in a 1% concentration with a compressed air foam system (CAFS) was applied to two different PV systems to determine the effectiveness of foam in blocking illumination and reducing or eliminating the electric shock hazard. Figure 43 illustrates the CAFS foam truck.

Figure 43 Fire truck with compressed air foam system

The two PV systems used were 1) the four framed-module array used above in the experiments with tarps, and 2) a three-laminate array. The laminates consisted of PV laminate modules mounted to metal pans (18 inches on center) typical of a standing seam metal roof construction. Each laminate was rated 68 watts (Pmax), with 23.1 V open circuit (Voc), 5.1 A short-circuit current (Isc). Three laminates were wired in series, and at standard test conditions, the output of the three-laminate array would be approximately 69 volts open circuit, 5 amps short circuit. Figure 44 illustrates the PV test specimens prior to application of foam.

Figure 44 Test roof with four-framed module and three-laminate arrays

Weather conditions at the time of these experiments were cloudy, with a solar irradiance of only 20 - 60 W/m^2, and a temperature of 7 ^{o}C. At the beginning of the test, and before any foam was applied, the four-famed module array had an open circuit voltage of 136 volts DC, and with the three-laminate array the open circuit voltage was 63 volts DC, measured with a solar irradiance of 60 W/m^2. The Class A foam (1%) was applied approximately 1 – 3 inches over the full exposed surface area of the modules and laminates. Figure 45 illustrates the PV test specimens during te application of foam.

Figure 45 Applying Class A foam (1%) with compressed air foam system

9.1.6. Results - Foam

Two minutes after the application of the foam the open circuit voltage on the four-framed module array was 117 volts, and for the three-laminate array the voltage was 48 volts. After 10 minutes the voltage on the modules remained at 117 volts, and the voltage on the laminates decreased to 40 volts. The test was stopped after 10 minutes because of increasing clouds and poor sun (solar irradiance of 20 W/m^2). Because of the clouds and limited sun, short circuit current measurements could not be made. It was noted that after 10 minutes the foam was still adhering well to the laminates, but gaps began to appear on the modules exposing glass surface. It was the consensus of those witnessing this experiment that this Class A foam was generally ineffective in blocking what little illumination the sun was providing that day. Figure 46 illustrates the CAFS foam layer deterioration.

Figure 46 - After 10 minutes, gaps appearing in foam over modules

9.2. Analysis

Under certain firefighting operations, such as overhaul, it may be necessary to block illumination from the sun in order to provide a safe work environment. This is because even when all of the required PV DC disconnects are opened, there still may be hazardous voltages at the array and associated wiring, and after a fire, exposed energized electrical PV wire and components may be present. Some techniques to block illumination may include the application of tarps and foams.

Some tarps can be very effective in reducing the electrical hazard to a safe condition, even on a very sunny day. However, the effectiveness of a tarp in blocking illumination to a safe level does not appear to be related to the quality or cost of the tarp. For example, an inexpensive 4 mil black plastic film was found very effective in blocking illumination from the sun almost completely, while a heavy red vinyl fire service salvage tarp was virtually ineffective in reducing a serious electric shock hazard to a string of modules in an array.

The application of ordinary Class A foam with a compressed air foam system did not prove to be effective or reliable in blocking sun to an array of PV modules. However, this Class A foam was not specifically intended for this sun blocking application. More research may be needed to find or develop specific foam products or other surface applied film technology that can be proven to be reliable and effective in blocking illumination to PV systems.

10. Severing of Conductors

During firefighting operations where photovoltaic systems are involved, a firefighter may be subjected an electrical shock hazard due to purposely or inadvertently cutting into or through live electrical PV conductors, or raceways containing live PV conductors. The requirements for PV wiring systems are contained in Article 690 of the NEC. For one- and two-family dwellings, the NEC permits PV system voltages up to 600 volts (DC). This is considerably higher voltage than the 120/240 volts (AC) typically found in dwelling units. For multi-family dwellings and other larger buildings, the PV system voltage can be even greater.

The NEC permits single conductor PV wire to be exposed in non-accessible outdoor locations, such as rooftops and ground mounted arrays. However, when PV circuits are run inside a building, the conductors must be contained in a metal raceway. When PV wires are run beneath a roof, they shall not be installed within 10 inches of the roof decking or sheathing, except where directly below the roof surface covered by PV modules and associated equipment. The NEC specifically notes that this 10 inch requirement is to prevent accidental damage from saws used by firefighters during roof ventilation. However, it is important to also note that this requirement is new for the 2011 version of the NEC, and older installations may not have complied with this new requirement.

10.1. Experiments with Severing of Conductors

To demonstrate the potential electrical hazards from the severing of conductors in PV systems, the following experiments were conducted. The tools used for severing included cable cutters and an axe for cutting through exposed conductor, and a rotary saw and a chain saw for cutting through raceway have conductors installed within.

10.2. Samples

Cable Cutter (Figure 47**) –** The cable cutter was 28 inch, with a 1-1/4 inch jaw capacity. The cable cutter was metal, and the handles were provided with non-metallic grips, however these grips were described as for providing comfort and no claims were made about electrical insulation. For test purposes, a wire connector was connected to the metal portion of the cutter to provide connection to a wire that would represent a firefighter coming in contact with the metallic conductive portion of the cutters. Figure 47 illustrates the cable cutter modified to include an electrical terminal for grounding.

Figure 47 Cable cutter

Axe (Figure 48**) –** The axe was 36 inch, with a fiberglass handle that was described as "will not conduct electricity." For test purposes, a wire connector was connected to the metal blade to provide connection to a wire that would represent a firefighter coming in contact with the metallic blade portion of the axe Figure 48 illustrates the axe used in the experiments.

Figure 48 Fiberglass handle axe

Rotary Saw (Figure 49**) –** The circular saw was a 14 inch fire rescue type saw with a metal diamond blade installed. For test purposes, a wire connector was connected to accessible metal hardware on the saw that was electrically continuous to the saw blade. This provided connection to a wire that would represent a firefighter coming in contact with the metallic portions of the saw that were electrically continuous to the blade. Figure 49 illustrates the rotary saw used in the experiments.

Figure 49 Rotary saw

Chain Saw (Figure 50) – The chain saw was a gas power chain saw with a standard 14 inch wood cutting chain. For test purposes, a wire connector was connected to accessible metal hardware on the saw that was electrically continuous to the saw chain. This provided connection to a wire that would represent a firefighter coming in contact with the metallic portions of the saw that were electrically continuous to the chain.

The source of PV power for these experiments was the test array described in Sec. 5.3 with modules wired in series to produce 1000 V open circuit, and 8 A short circuit. The negative side of the array was connected to ground, and also in the grounded negative side was a 500 Ohm resistor to represent a body impedance, and a metering shunt to measure current. A lead from the negative was also connected to the tool being used for the cutting through the wire connector as described above. Figure 50 illustrates the chain saw used in the experiments.

Figure 50 Chain Saw

10.3. Experiments with Cable Cutters

For this experiment, the cable cutters were used to severe an exposed wire, Type USE-2, No. 10 AWG, which was connected to the positive side of the 1000 V array. For the first test, a slow cut was made through the wire with the cutters. This produced a current in the circuit of 2 A.

For the second experiment, this first experiment was repeated, but with making a fast cut through the wire with the cutters. This produced a current in the circuit of 2 A for about 200 milliseconds, and the current reduced to zero by 300 milliseconds. Figure 51 illustrates arcing to grounded cable cutter.

Figure 51 Cutting wire with cable cutter

10.4. Experiments with Axe

For this experiment, the axe was used to severe an exposed wire, Type USE-2, No. 10 AWG, which was connected to the positive side of the 1000 V array. For the first test, a slow blow was made through the wire with the axe. This produced a current in the circuit of 1.5 A for about 180 milliseconds, and the current reduced to zero by 220 milliseconds.

For the second test, this first test was repeated, but with making a fast blow through the wire with the cutters. This produced a current in the circuit of 1.5 A for about 40 milliseconds, and the current reduced to zero by 50 milliseconds. Figure 52 illustrates damage to axe after severing a live conductor.

Figure 52 Carbon deposit from arcing on axe blade after severing conductor

10.5. Experiments with Rotary Saw

For this experiment, the rotary saw was used to severe a metal raceway, ½ inch electrical metallic tubing (EMT) with a No. 12 AWG copper Type THHN wire installed within. The No. 12 AWG wire was connected to the positive side of the 1000 V array, and the metal tubing was connected to ground. Attempting to measure current with this experiment with the rotary saw presented challenges due to the intense electrical noise being produced by the engine. However, in this scenario with the ungrounded positive conductor inside the grounded metal raceway, the current had two paths, one through the grounded wire connected to the saw and 500 Ohm resistor to represent the firefighter, and the other through the grounded metal tubing Figure 53 illustrates rotary saw cutting through EMT.

Figure 53 Rotary saw cutting through EMT

For this second experiment, the rotary saw was used to severe a non-metallic conduit, ½ inch Type PVC, with two No. 12 AWG copper Type THHN wires, one positive and one negative, installed within. Cutting through the nonmetallic conduit produced a current of 8 A. In this scenario there was no path to ground through a metal raceway. After the cut was made, arcing continued between the positive and negative conductors, resulting in an open flame. Figure 54 illustrates rotary saw cutting through nonmetallic conduct. Figure 55 illustrates ignition of the nonmetallic conduit.

Figure 54 Cutting through nonmetallic conduit

Figure 55 Open flame from arcing

For this third experiment, the rotary saw was used to severe a flexible metal conduit, ½ inch Type FMC, with two No. 12 AWG copper Type THHN wires, one positive and one negative, installed within. The flexible metal conduit was secured to a wood stud. After the cut was made, arcing continued between the positive and negative conductors, resulting in ignition of the wire insulation and the wood stud to which the flexible metal conduit was attached.


Figure 56 Cutting through flexible metal conduit


Figure 57 Open flame from arcing

For this fourth experiment, the chain saw was used to sever a flexible metal conduit, ½ inch Type FMC, with two No. 12 AWG copper Type THHN wires, one positive and one negative, installed within. After the cut was made, arcing continued between the positive and negative conductors, resulting in an open flame igniting the wire insulation and the wood stud to which the flexible metal conduit was attached. It was also noted that the rotating chain of the saw ripped the conductor out of the flexible armor, resulting in an exposed conductor after the cut was made. Figure 58 illustrates the chain saw cutting through flexible metal conduit.   Figure 59 illustrates ignition as a result of the severing of the conductors.


Figure 58 Cutting through flexible metal conduit


Figure 59 Open flame from arcing

Figure 60 illustrates the exposed conductors resulting from the chain saw severing the conduit.

Figure 60 Exposed conductor from action of chain cutting

10.6. Analysis

With some operations, it may be necessary to purposely cut wires and cables to help reduce the risk of an electric shock. Special electrician's tools and gloves are available for this purpose when an electrical worker finds it necessary to cut an energized conductor. Although firefighters may be provided with cable cutters for cutting wires, they may not be adequate for cutting energized conductors, as is sometimes the case with PV systems that cannot be completely deenergized. A shock hazard could exist if, for example, the firefighter was grounded, and was cutting an ungrounded energized conductor, and direct contact was made with the metal portion of the cable cutters during the cutting operation.

Experiments showed that in a scenario such as cutting energized wires, current sufficient to cause a dangerous electric shock. The length of time this current was present was often shortened because of the complete severing of the wire. This could eliminate some potential hazards, such as lock-on and the inability to let go.
Some firefighting operations also require roof ventilation and the use of a cutting tool such as rotary saw or chain saw to cut through the roof decking material. A hazard could exist if the firefighter is not aware of energized conductors, such as PV wires installed in metal raceways in the attic, are present. Although the firefighter operating these tools is not often in contact with a metal portion of the tool that may become energized when contact with the energized conductor is made, these tools are not typically tested for their electrical insulation properties. Experiments also showed that energized PV conductors of opposite polarity are in the same raceway and severed, after the cutting takes place it is possible for the arcing to continue and result in open flaming and ignition of materials. A chain saw also poses the risk of exposing live conductors from the ripping and pulling action of the chain against the wire.

11. Shock Hazard from Damaged PV Modules and Systems

With a fire scene where photovoltaic systems are involved, a firefighter may be subjected to an electrical shock hazard due to damaged PV system components, as live electrical parts may become exposed. Damage to these PV system components can occur because of heat from the fire itself, or from other occurrences such as a firefighter stepping or falling onto a module, striking a module with an axe or pike pole, or attempting to remove a module from its intended mounting means. Some of this damage may occur during the fire, while other damage may occur during overhaul operations.

The power generation parts of a PV module typically consist of solar cells and live electrical copper bus material to interconnect these cells. These live parts are usually “sandwiched” between a glass or hard plastic top material called the superstrate, and a thinner polymeric backing material called the substrate. When either the superstrate or substrate material is damaged and broken through, the live copper bus and solar cell material can be contacted. When sufficient voltage and current is present, contact with these energized electrical parts could result in an electrical shock hazard to the firefighter. Figure 61 illustrates typical construction of a metal framed solar module.

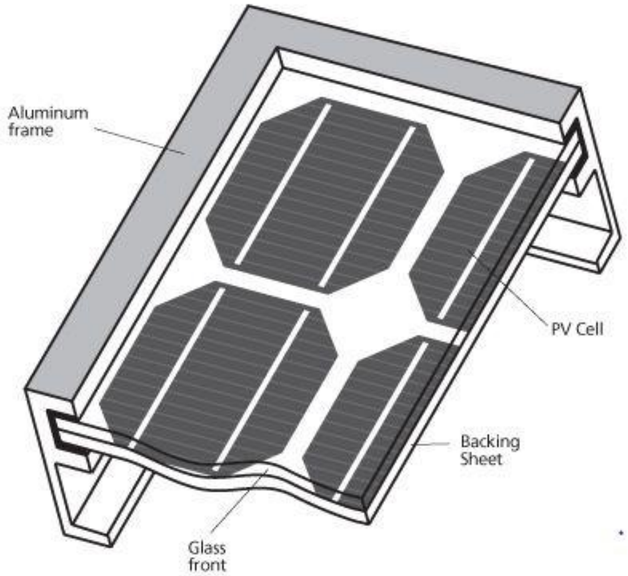

Figure 61 Framed module with solar PV cells and copper bus sandwiched between glass front (superstrate) and backing sheet (substrate)

11.1. Experiments with Damage to PV Components

To demonstrate the potential electrical hazards from the damaging of PV modules and similar system components, experiments were conducted to assess the hazard associated with typical firefighter tools breaching a PV module. The tool used for damaging the PV components was the pick end of a metal axe. This was considered to be representative of other tools, such as a pike pole, Halligan tool, roof hook and similar tools that may be used during firefighting and overhaul operations.

Axe – The axe was 36 inch, with a fiberglass handle that was described as “will not conduct electricity.” For test purposes, a wire connector was connected to the metal blade to provide connection to a wire that would represent a firefighter coming in contact with the metallic blade portion of the axe. Figure 62 illustrates the axe used in the experiments.

Figure 62 Fiberglass handle axe

The source of PV power for these tests was the test array described in Sec. 5.3, with modules wired in series to produce 1000 V open circuit, and 8 A short circuit. The negative side of the array was connected to ground. A lead from the negative was also connected to the axe blade through the wire connector as described above.

11.1.1. Experiments with PV Framed Modules

For this experiment, the poke end of the axe was used to penetrate the glass front of a PV framed module with a striking blow. This produced arcing and flame, as the grounded metal axe blade was making contact with the ungrounded (positive) energized metal parts below the glass. Figure 63 and Figure 64 illustrate arcing / ignition and damage to the PV module after being struck by the axe pick.

Figure 63 Arcing and flames from axe damage

Figure 64 Resulting hole in module glass

11.1.2. Experiments with PV Laminate Modules

For this experiment, the poke end of the axe was used to strike the front of a PV laminate mounted to a metal pan. The striking blow was such that the axe pike penetrated both the PV laminate and the metal pan material. This caused the metal pan to become energized at the positive potential of the array. To further demonstrate the hazard here, a metal Halligan tool was inserted into the near-by earth ground. A voltmeter was then placed between the metal pan and the Halligan tool. A potential of 883 volts was measured on the meter. Figure 65 and Figure 66 illustrate the configuration of the axe and Halligan tool during the experiment.

Figure 65 Axe penetrates laminate

Figure 66 Halligan tool imbedded in ground

Figure 67 illustrates the voltage measured during the experiment.

Figure 67 Voltage measured between metal pan and earth

11.1.3. Experiment with PV Shingle Modules

For this experiment, the poke end of the axe was used to strike the front of a PV shingle. This produced arcing and flame, as the grounded metal axe blade was making contact with the ungrounded (positive) energized metal parts within the shingle. This damage became even more evident when a Halligan tool was used to pry the shingle off the roof, and the arcing underneath was exposed. Figure 68 and Figure 69 illustrates damage to the roofing shingle sample and subsequent arcing and ignition.

Figure 68 Axe pike damages PV shingle

Figure 69 Resulting arcing and flame

11.1.4. Analysis

When firefighting operations involve a building with PV installed, it is very possible that PV system components, such as PV modules, may become damaged during the fire itself, or during overhaul activities. This damage may be the result of a firefighter's metal tools striking or punching through one or more layers of the PV module. In a typical PV module (or laminate or shingle for example), between the glass or hard plastic superstrate (front) layer and the thinner substrate (back) layer, are located conductive live electrical parts and copper bus material forming the power generation layer. If a firefighter comes in direct contact with these exposed electrical parts, either between plus “+” and minus “-“, or between ground and an ungrounded live part, an electrical shock hazard would exist.

Experiments showed that in a scenario such as punching through the glass superstrate of a PV module with an axe poke, the conductive parts of the PV module layer could easily be contacted. This will energize the metal axe blade, and if the firefighter were to make direct contact with this metal blade, a serious electrical shock could occur. Similar scenarios using other typical firefighting tools, such as a metal pike pole, roof hook, or Halligan tool, would likely put the firefighter in the same risk of electric shock. Experiments with a PV system consisting of PV laminate material mounted to a metal pan, typical of a metal seam roof, produced an additional electrical shock hazard when the metal pan itself became energized from the axe pike penetrating both the PV laminate and the metal pan.

In addition to the electric shock hazard, these tests also demonstrated the potential for an electrical fire hazard as the metal tool penetrated the PV layers and created arcing between live parts of opposite polarity. This arcing often resulted in ignition and open flaming.

12. Assessment of PV Power During Low Ambient Light, Artificial Light, and Light from a Fire

PV systems consist of devices, such as modules, that use solar cells to generate DC electricity when exposed to light. Sunlight is the main source of illumination for a PV system, but it may not be readily known if a PV system is generating electricity when exposed to sources of light other than natural sunlight. This is important for firefighters to know when assessing the electrical safety hazard of a PV system when light other than sunlight is present.

To assess the power from a PV system with light conditions from other than sunlight, experiments were conducted using artificial light from fire trucks that might be used for scene lighting during a nighttime fire event, light being given off by the fire itself, and light from a low ambient source, such as a full moon.

12.1. Experiments with Artificial Light from a Fire Truck

Many fire services use special light trucks to provide fire ground illumination during nighttime firefighting operations and overhaul activities. These special trucks can provide several kilowatts of light power, and if used at a fire scene where PV is present, such as on the roof, the firefighters may unknowingly believe that the PV power source is not producing any hazardous electricity.

For these experiments two different light trucks currently used by local fire departments were employed. Truck No. 1 consisted of eight (8) 1500 watt lights mounted on short vertical poles attached to the truck bed (12 kW total), and four (4) 1500 watt lights mounted on an articulated boom (6 kW total). The total light wattage output of truck No. 1 was 18 kW. Truck No. 2 consisted of four (4) 1500 watt lights mounted on the truck bed (6 kW total), and three (3) 1500 watt lights on the articulated boom (4.5 kW total). The total light wattage output of truck No. 2 was 10.5 kW. Using both Truck No. 1 and Truck No. 2, the total available light output could be 28.5 kW.

To assess this hazard, the main test array (26 modules) was used. The experiments were conducted after sunset, and the ambient light conditions (natural darkness) were producing 48 volts and no current at the output of the array. Ambient weather conditions were mostly cloudy and 40 F at the time of the testing.

A series of experiments was conducted by using either Truck No. 1 or No. 2, or both, with all or some of their lighting illuminated. Measurements of the array's open circuit voltage and short circuit current were made with the trucks' at various distances from the array. Distance was measured from the edge of the truck to the front edge of the array, with the front edge of the array only a few feet above grade. Truck No. 1 was positioned 25 and 50 feet from the array depending on the experiment. At 25 feet, Truck No. 1 was positioned in front of the array, and at 50 feet, Truck No. 1 was at about a 45 degree angle from the array.

Truck No. 2 was positioned 38 and 75 feet from the array depending on the experiment. At 38 feet, Truck No. 1 was positioned in front of the array, and at 75 feet, Truck No. 2 was at about a 45 degree angle from the array. Figure 70 illustrates array illuminated by Fire Department light truck.

Figure 70 - Array being illuminated by Light Truck No. 1

Figure 71 illustrates Fire Department light truck boom mounted lights.

Figure 71 Light Truck No. 2 boom lights

Figure 72 illustrates array illuminated by both light trucks, boom and bed mounted lights.

Figure 72 Both trucks lighting the array

12.1.1. Results

Ten different experiments were conducted as shown in Table 18 below. For each experiment, the open circuit voltage and short circuit current was measured. Since the impedance of the array would be large because of the low current (power) available, no body impedance resistor was used in the circuit as it would not have made a significant difference. To verify this, Test No. 9 was repeated with a 500 Ohms resistor in the circuit, and the short circuit current only reduced from 49 to 46 milliamps. Table 18 summarizes the results of the Fire Department light truck illumination experiments.

Table 18 – Results of experiments with fire truck illumination

1000 Volt Array with Night-Time Illumination from Fire Truck(s) Lighting

Test	**Truck #1 Bed 12 kW Boom 6 kW**	**Truck #2 Bed 6 kW Boom 4.5 kW**	**Total Lighting kW**	**Distance from Array (Feet)**	**Open Circuit Volts**	**Short Circuit MilliAmps**	**Hazard**
			None		48	0	**Safe**
1	Bed + Boom		18	25	812	132	**Lock On**
2		Bed + Boom	10.5	38	780	88	**Lock On**
3		Boom	4.5	38	738	50	**Lock On**
4	Bed + Boom	Bed + Boom	28.5	25 & 38	836	212	**Lock On**
5	Partial Bed		3	25	657	22	**Perception**
6	Partial Bed		1.5	25	575	11	**Perception**
7	Bed + Boom		18	50	735	37	**Perception**
8		Bed + Boom	10.5	75	700	22	**Perception**
9	Bed + Boom	Bed + Boom	28.5	50 & 75	773	49	**Lock On**
10	Partial Bed		1.5	50	340	1.5	**Safe**

12.2. Experiments with Light from a Fire

If a fire is burning on or near a roof that has PV modules installed, it would be of interest to know if light from the fire could produce enough illumination to cause the PV array to produce a hazardous level of electricity. To explore this possibility, experiments were conducted at UL's large scale fire test facility in Northbrook, IL.

A special test fixture was constructed using two of the PV framed modules from the main test array (230 W, nominal 37 V open circuit, 7.5 A short circuit). The modules were mounted side-by-side on a mobile cart that could be moved various distances incident to the fire. The fire was created by using 12 wood skids, in two rows of six, side-by-side. At various distances from the fire, open circuit voltage was measured on one module, and current through a 500 Ohm resistor, to represent a body impedance, was measured on the other module. During these experiments, the lab area was completely darkened except for some overhead lights that were not directly incident to the face of the modules, but were left on for safety purposes. Figure 73 Test fixture with modules approaching fireillustrates the test configuration for illumination of the PV module by fire experiments.

Figure 73 Test fixture with modules approaching fire

12.2.1. Results

Measurements of the PV output were recorded beginning at 75 feet from the skids were ignited and allowed to burn for five minutes. The final measurements were recorded with the PV modules positioned 15 feet from the fire after it had been burning for ten minutes. The results of these measurements are shown below in the Table 19 below.

Table 19 Results of experiments with light from a fire

Light from a Fire (Single Module)

Distance from Fire (Feet)	Open Circuit Volts	Short Circuit MilliAmps	Hazard
75	30	52	Lock On
50	31	57	Lock On
40	32	59	Lock On
15	33	62	Lock On
Full Sun	37	7500	

12.3. Experiments with Low Ambient Light

PV modules generate electricity when exposed to light. Direct sunlight is the main source of light for PV systems, and these PV systems will be generating the most amount of power on clear days when the sun is directly overhead and the rays of the sun are incident to the surface of the modules. As the sun rises in the morning, the PV system will begin to steadily generate increasing electricity until peak power is achieved, and then begin to diminish as the sun sets in the evening. Some PV systems are designed to rotate the modules and track the sun as it moves across the sky from east to west, and thus increase the overall efficiency of the PV system.

It may also be possible for a PV system to generate some amount of electricity when exposed to indirect sunlight, or artificial light. It is often assumed that once the sun sets, the PV system is no longer generating electricity, and thus no danger of an electrical hazard is present. Although this is most often true, artificial light such as that described above from fire truck scene lighting, or light from a fire, could present an electrical shock hazard. Indirect natural light, such as that from a rising or setting sun, or even a full moon, could be of concern.

To record the electrical output from a typical PV system over a 24 hour period, the following experiment was conducted. Two identical four framed-module arrays were used that were located on the rooftop of a building. Each module was rated 44 V open circuit (Voc), 8.5 A short-circuit current (Isc). The four modules from each array were wired in series for a total array open circuit voltage of 176 VDC.

The experiment was conducted from noon (12:00 hours) on February 18, to noon on February 19, 2011. A full moon occurred on February 18. Sunset on February 18 was 17:27, and sunrise on February 19 was 6:41 am. Solar noon occurred at 12:05 pm. The weather conditions were mostly clear, with a few passing clouds, and temperatures ranging from +6 C during the day to -4 C at night.

For this 24 hour period, open circuit voltage was recorded on one array, and short circuit current was recorded on the other array. Recordings were taken once per minute.

12.3.1. Results

The results of the 24 hour period array open circuit voltage and short circuit current measurements during a full moon are shown. At 17:46 hours, the short current of the array reduced to less than 2 mA. This was 19 minutes after sunset. At 6:24 hours the next morning, the short circuit current of the array rose to greater than 2 mA. This was 17 minutes before sunrise. At sunrise the short circuit current of the array was 38 mA.

With no artificial light, and no other source of natural light other than that reflected from a full moon, there was no electrical hazard from the array from a time period of approximately 20 minutes after sunset, and until 20 minutes before sunrise the next morning. Figure 74 illustrates the open circuit voltage for a 24 hour period during a full moon. Figure 75 illustrates the short circuit current for for a 24 hour period during a full moon.

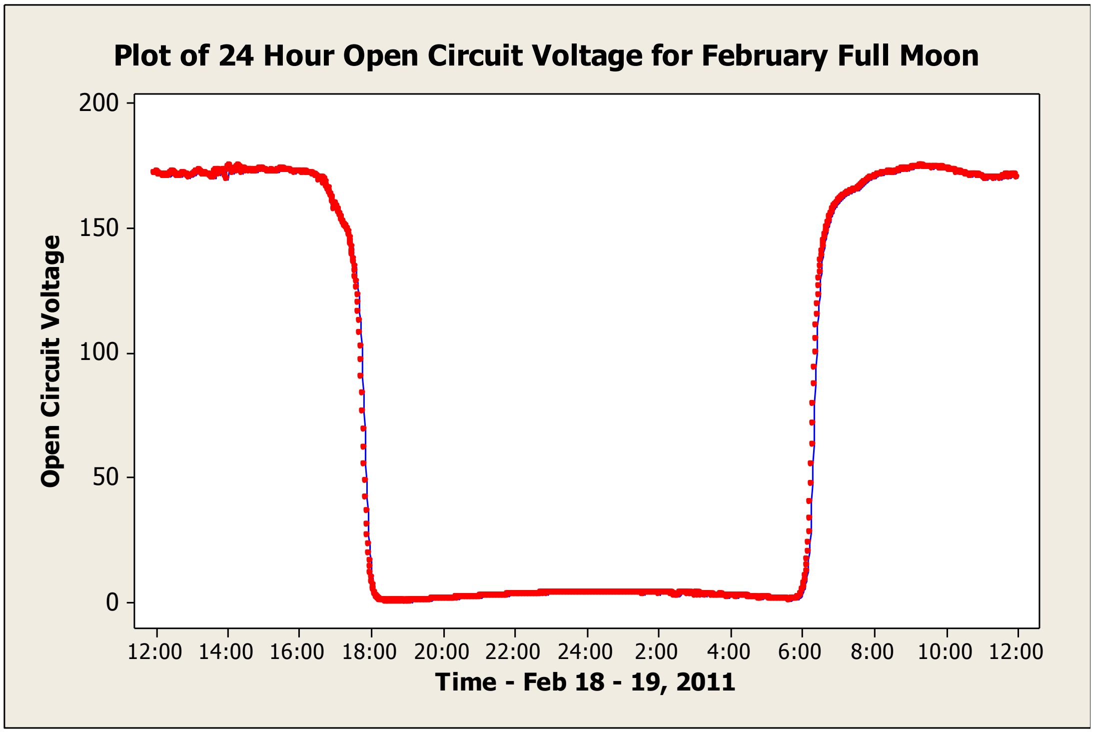

Figure 74 Plot of array open circuit voltage for 24 hour period with full moon

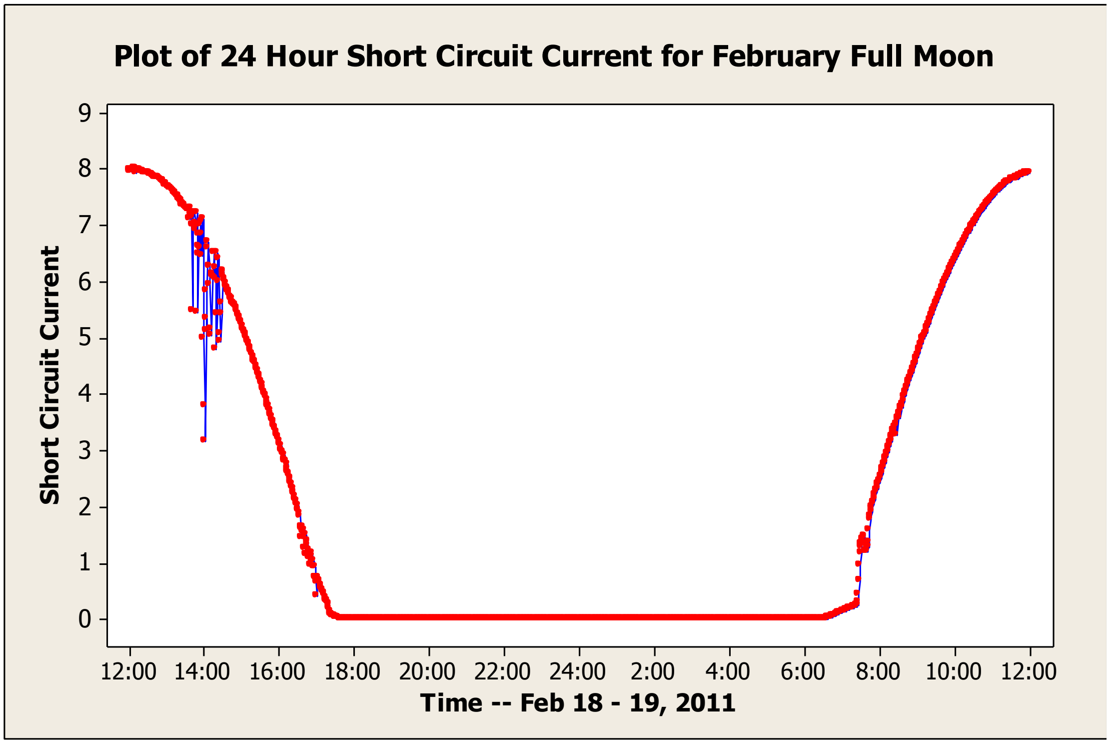

Figure 75 Plot of array short circuit current for 24 hour period with full moon (scattered clouds noted from 13:00 – 15:00 hours on plot)

12.4. Analysis

Artificial Light from a Fire Truck - In most cases under these artificial lighting conditions, the light trucks were able to produce enough illumination to cause an electrical shock hazard. Although significantly less than the 240 milliamp threshold for ventricular fibrillation of the heart, both of the trucks were each able to produce enough light to cause the array to produce over 40 milliamps, the “lock-on” threshold, even at distances as far away as 38 feet from the array.

Light from a Fire - Under these test conditions, the illumination from this fire was able to produce currents of over 40 milliamps, the “lock-on” threshold at distances as far away as 75 feet from the fire.

Low Ambient Light – With no artificial light, and no other source of natural light other than that reflected from a full moon, there was no electrical hazard from the array from a time period of approximately 20 minutes after sunset, and until 20 minutes before sunrise the next morning.

13. Potential Shock Hazard from Fire Damaged PV Components and Systems

During a fire event, a PV array including modules, components, and their associated wiring may be subjected to thermal and mechanical stresses that can result in damaged energized devices and wiring. Direct contact with these exposed energized PV system components could lead to a firefighter being endangered due to an electrical shock hazard.

PV systems, which typically consist of an array of PV modules, are often associated with buildings, where the PV system components can either be mounted to the building, such as on the roof, integrated into the building structure, or mounted nearby on the ground. When a building is subjected to a fire, originating either within the PV system itself or from some other source, it is possible for the PV system to become damaged to the extent that exposed energized PV components and wiring may become present. This situation could present an electrical shock hazard to the firefighters during suppression, ventilation and overhaul operations. To investigate the potential for this electrical shock hazard, the following experiments were conducted.

13.1.1. PV Systems Exposed to Fire

A series of experiments were conducted at the Delaware County Emergency Services Training Center in Sharon Hill, PA. Two concrete bunkers, each measuring 36 by 21 by 8 feet high were built on a concrete slab. A wood truss roof was then constructed on each bunker; with a resulting surface area of approximately 36 by 12 feet per side with a 5/12 pitch. The bunker had provisions for door and window openings on three sides which could be closed with cement board for test purposes. Figure 76 and Figure 77 illustrate the test fixture for the full scale array fire experiments.

Figure 76 Test bunker – side with window opening

Figure 77 Test bunker – font gable Side

Figure 78 illustrates the general dimensions of the building’s outer walls.

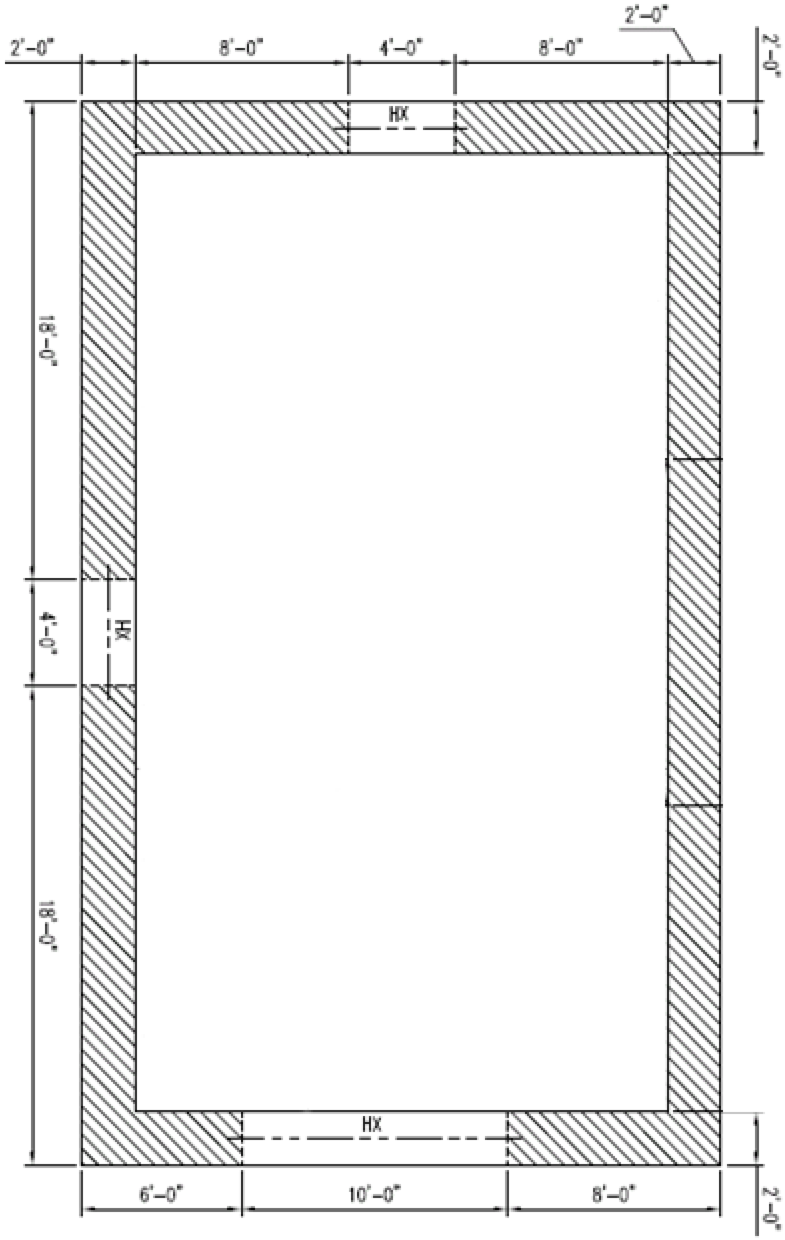

Figure 78 Structure floor plan

13.1.2. Instrumentation and Uncertainty

The measurements taken during the experiments included gas temperature, within the compartment, surface temperatures on the roof and underside of the PV modules, voltage and video recording. Gas temperatures were measured with bare-bead, Chromel-Alumel (type K) thermocouples, with a 0.5 mm (0.02 in) nominal diameter. Thermocouple arrays were located in 2 locations within the fire compartment. All of the thermocouple locations had an array of thermocouples with measurement locations of 0.03 m, 0.3 m, 0.6 m, 0.9 m, 1.2 m,1.5 m, 1.8 m and 2.1 m (1 in, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft and 7 ft) below the truss in the fire compartment. The standard uncertainty in temperature of the thermocouple wire itself is ± 2.2 °C at 277 °C and increases to ± 9.5 °C at 871 °C as determined by the wire manufacturer. Figure 79 illustrates the location of the thermocouples and fuel packages.

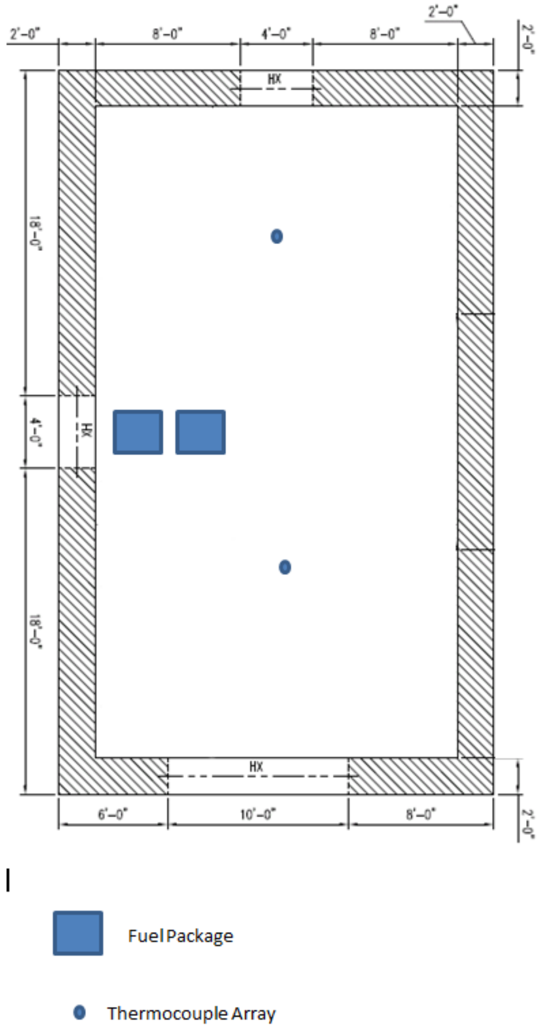

Figure 79 Measurement and fuel package locations

Figure 80 illustrates the location of the roof and array thermocouples.

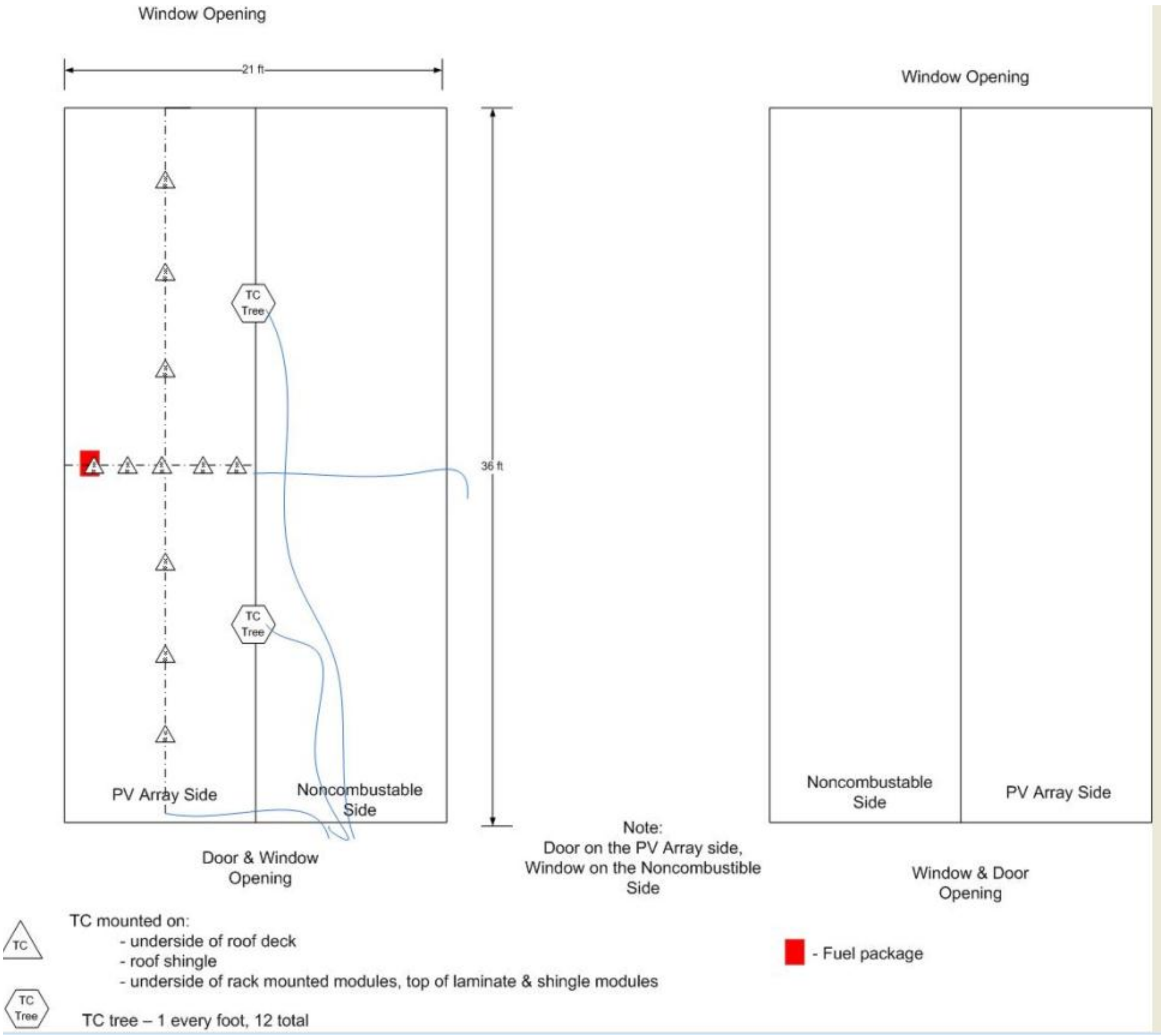

Figure 80 Measurement and fuel package locations

Video cameras were placed inside and outside the structure to monitor both smoke and fire conditions throughout each experiment. For the first three experiments, six video camera views were recorded during each experiment. Two outside views recorded the experiment from the rear and the front of the structure. Two inside views recorded the fire conditions with the test fixture from a location at the rear of the compartment looking forward and from a location at the front of the compartment looking back. Two additional views recorded the roof and PV array from an elevated position and included an infrared camera.

For the subsequent experiments involving a compartment fire venting from a window and debris fire under the array, eight views were recorded. Six views as described earlier with two additional views recording the area under the rack mounted array. Both cameras were positioned along the centerline of the roof, one view from the ridgeline forward to the edge of the roof, one from the front of the structure looking toward the rear. Figure 81 illustrates a quad video view of the room of content fire experiments. Figure 82 illustrates a quad video view of the debris fire under array experiments.

Figure 81 Quad Video 1 - Compartment / Roof Fire

Figure 82 Quad Video 1 – Window Vent & Debris Fire

13.1.3. Fuel Load

The fuel load was selected to represent a room of content fire and of sufficient energy to attain flash over conditions within the test fixture and progress to a structure fire. Two stacks of wood pallets were positioned in the test fixture. Each stack of pallets contained 6 pallets with a weight range of 210 lb. to 240 lb. per stack for a combined fuel package average weight of 450 lb.

The fuel packages was located in the center of the structure and biased to the left wall. Figure 61 shows the relative locations of the fuel packages. The center of the fuel package was located 9 ft from the end walls and 10 ft from the side walls. The fire was ignited with two standard UL igniters made up of gauze in a plastic bag, soaked in 8 ounces of gasoline. Each igniter weighed 0.5 lb., and they were placed in the separation of the pallets with one in each stack, on opposite sides. To light the igniters a torch was touched to them. The fire grew and was allowed to burn until the structural integrity of the roof assembly was compromised at which time it was extinguished. The igniters were lit remotely with a thin wire wrapped around a pack of matches that was electrically charged until the heat from the wire ignited the matches and in turn ignited the igniters. Figure 83 illustrates the UL igniter. Figure 84 illustrates the position of igniter within the wood skid fuel package.

Figure 83 UL Igniter

Figure 84 - Igniter In Wood Skids

13.2. Fire Experiments with Modules of Glass on Polymer Metal Frame, Laminates, and Solar Shingles

Fire experiments were conducted with three different types of PV module systems installed on the roof; framed glass on polymer modules, laminates, and solar shingles as follows:

13.2.1. Glass on Polymer Metal Frame Modules –

The fire test array with glass on polymer metal frame samples consisted of modules rated 230 W as follows:

Open-circuit (Voc) - 48.7 V
Short-circuit current (Isc) - 5.99 A
Voltage at maximum power (Vmp) - 41.0 V
Current at maximum power (Imp) - 5.61 A

Each module measured 5 ft. 1 in. by 2 ft. 7 in. mm, with a depth of 2 in. and weight of 33 lb. Each module contained 72 monocrystalline silicon cells. The construction included three by-pass diodes, and a front tempered glass with aluminum frame.

The test array consisted of 20 modules, with two parallel strings of 10 modules wired in series. Total power of the array at standard test conditions was 4600 watts, with a voltage of 410 volts and 11.2 amps. The open circuit voltage of the array was 487 volts DC, and the short circuit current was 12 amps DC.

The modules were mounted to the roof in two horizontal rows of 10 each, with an aluminum rail mounting system. The modules in the top row were identified as A1 through J1 left to right across the roof from ground, and the bottom row A2 through J2. The rack mounting system was such that the top of the module was 6 inches off the roof surface, and the bottom of the module frame was 4-1/2 inches off the roof surface. The roof surface under the modules consisted of ¾ inch OSB decking covered with 15 lb felt paper and black asphalt shingles. The other half of the roof was decked with cement board to help force the fire to burn through the PV side of the roof.

The “home run” wire was installed in electrical metallic tubing (EMT) mounted along the inside of the roof near the peak. The wire from the module strings transitioned from PV wire to THHN wire at a box located on the roof. The THHN wire was installed in EMT from this box to the inverter located in the side of the bunker near ground level. The string conductors were wired through a disconnect switch to an inverter rated 4000 watts. The inverter had a 1 amp GFDI fuse installed. The inverter was connected to a 208 volt ac, single phase grid tie. The DC PV system was positive grounded, and the aluminum rails and the aluminum frames of the modules were connected to equipment ground. For test purposes, voltage sense leads were attached to the module leads to measure individual module output voltage during the test, as well as the measurement of array voltage and array current at the inverter.

Figure 85 and Figure 86 illustrate the PV array mounted on the test structure. Figure 87 illustrates the installation of the metal framed modules. Figure 88 illustrates the grounding method of the array. Figure 89 provides a view of the raised, rack mounted array and combiner box.

Figure 85 Completed framed module array

Figure 86 Framed module array from above

Figure 87 Installing framed modules

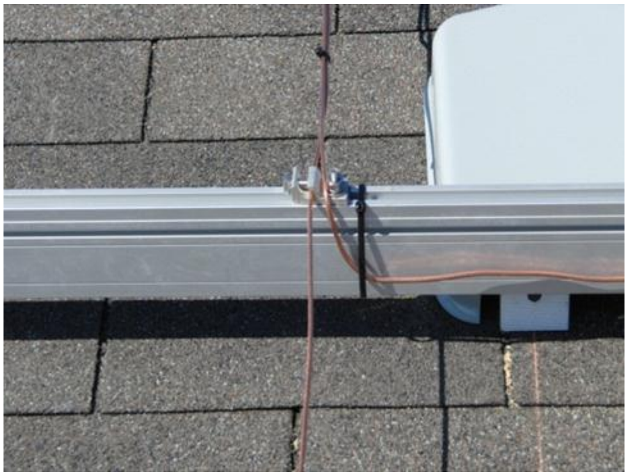

Figure 88 Grounding system for rails

Figure 89 Modules mounted off roof / EMT to inverter

13.2.2. Laminate Modules –

The fire test array with laminate modules consisted of flexible adhesive backed PV laminates mounted to metal pans (18 inches on center) typical of a standing seam metal roof construction. Each laminate was rated 68 W as follows:

Open-circuit (Voc) – 23.1 V
Short-circuit current (Isc) – 5.1 A
Voltage at maximum power (Vmp) – 16.5 V
Current at maximum power (Imp) – 4.13 A

Each laminate measured 9 ft. 4 in. by 1 ft. 4 in. with a depth of 0.15 in. and weight of 8 lb. 9 oz. Each laminate contained 11 amorphous silicon cells connected in series, with a by-pass diode connected across each cell.

The test array consisted of 21 laminates in a single series string. The laminates were identified 1 through 21, left to right across the roof from ground. Total power of the array at standard test conditions was 1428 watts, with a voltage of 346.5 volts and 4.1 amps. The open circuit voltage of the array was 485 volts DC, and the short circuit current was 5 amps DC.

The laminates were adhered to metal pans, with each laminate in a single pan, and the pans seamed together. Two pans at each end did not contain laminates but were provided to completely cover the roof side. The roof surface under the modules consisted of ¾ inch OSB decking covered with 15 lb felt paper. The other half of the roof was decked with cement board to help force the fire to burn through the PV side of the roof.

The leads from the junction box of the laminates were wired on the inside of the roof. The “home run” wire was installed in electrical metallic tubing (EMT) mounted along the inside of the roof near the peak. The PV array was wired through a disconnect switch to an inverter rated 4000 watts, and located on the side of the bunker near ground level. The inverter was connected to a 208 volt ac, single phase grid tie. The DC PV system was negative grounded, and the metal pans were not connected to equipment ground. For test purposes, voltage sense leads were attached to the laminate leads to measure individual laminate output voltage during the test, as well as the measurement of array voltage and array current at the inverter.

Figure 90 illustrates the installation of the laminate PV / standing seam metal roof. Figure 91 illustrates the completed installation of the laminate PV / standing seam metal roof array. Figure 92 illustrates the wiring method. Figure 93 provides a view of the inverter location on the test structure.

Figure 90 Installing laminates and metal roof

Figure 91 Overhead view of laminate roof

Figure 92 Laminate lead wires and home run

Figure 93 Inverter/disconnect near ground

13.2.3. Solar Shingle Modules –

The fire test with solar shingle modules consisted of building integrated solar shingles. Each shingle was rated 50 W as follows:

Open-circuit (Voc) - 8.7 V
Short-circuit current (Isc) – 8.07 A
Voltage at maximum power (Vmp) – 6.79 V
Current at maximum power (Imp) – 7.65 A

Each shingle measured 47 x 17-1/4 inches with a depth of 17/32 inches and weight of 12 lbs. Each module contained 14 polycrystalline silicon cells and one by-pass diode.

The test array consisted of 68 shingles in a single series string, plus four non-connected shingles to form a 9 x 8 array. The shingles in the top row were identified as A1 through I1, left to right across the roof from ground. The shingles in the next row down were identified as A2 through I2, etc., with the final row being A8 through I8. Total power of the array at standard test conditions was 3400 watts, with a voltage of 462 volts and 7.7

amps. The open circuit voltage of the array was 592 volts DC, and the short circuit current was 8 amps DC.

The shingles were secured to the roof with screws. The roof surface under the modules consisted of ¾ inch OSB decking covered with 15 lb felt paper. The other half of the roof was decked with cement board to help force the fire to burn through the PV side of the roof.

The leads from the junction box of the shingles, and the home run wire, were routed within the integral shingle wireway. The PV array was wired through a disconnect switch to an inverter, rated 4000 watts, and located on the side of the bunker near ground level. The wires from the PV array on the roof to the inverter were installed in EMT. The inverter was connected to a 208 volt ac, single phase grid tie. The DC PV system was negative grounded, and there were no connections to an equipment ground. For test purposes, voltage sense leads were attached to the solar shingle leads to measure individual shingle output voltage during the test, as well as the measurement of array voltage and array current at the inverter. Figure 94 illustrates the installation of the solar shingle modules. Figure 95 provides a view of the completed solar shingle array. Figure 96 illustrates the solar shingle.

Figure 94 Installing solar shingles

Figure 95 Overhead view of shingle roof

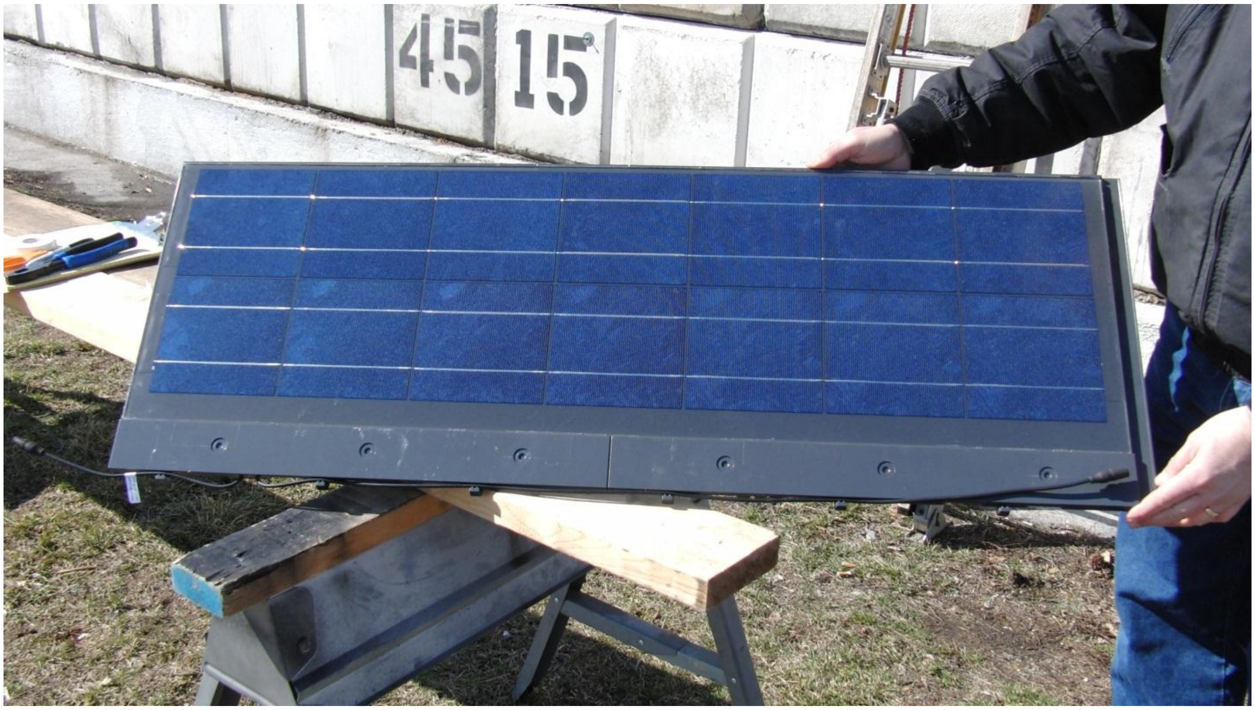

Figure 96 Individual solar shingle

13.3. Experiments with Glass on Polymer Metal Frame PV Modules

The fire experiments with PV metal-framed modules were conducted on March 4, 2011. The weather conditions at the time of the test were partly cloudy and 40 degrees F.

The fire load consisted of 20 wood pallets, stacked in two rows of 10 each. The wood pallets were located at ground level inside the bunker at the approximate center of the roof under the PV modules. The total weight of the 20 wood pallets was 828 lbs.

The initial power conditions being produced by the PV array at the beginning of the experiment were 3450 watts, 402 volts DC, and 224 volts ac. The wood pallets were ignited with the standard UL igniter. The following observations were made as the fire test progressed:

After 2 minutes (elapsed time), the pallets were fully engulfed in flames, and some smoke was observed coming out the door and window. After 4 minutes some smoke was observed under the panels, but there was no breach in the roof. At 6 minutes 40 seconds, the ground-fault detection and interruption fuse within the inverter opened, and the inverter turned off. The density of the smoke continued to increase, and after 9 minutes 30 seconds some flames were observed coming from the top of the roof. At 12 minutes there was open flaming at the back gable end, and at 13 minutes some water was applied at that location to help force the fire towards the center of the roof structure. At 16 minutes there was some horizontal sag observed in the modules between the upper and lower strings, and at 17 minutes flames breached completely through the roof. At 18 minutes 30 seconds, the roof and PV array collapsed into the building, and water was applied to extinguish the fire.

Figure 97 provides a view of the test array prior to the start of the experiment. Figure 98 illustrates the interior of the test building. Figure 99 provides a view of the door and window during the experiment. Figure 100 illustrates smoke venting from the test structure.

Figure 97 Pre-Test conditions with modules

Figure 98 Wood pallets ready for ignition

Figure 99 Wood pallets fully engulfed in flames

Figure 100 Some smoke coming from roof

Figure 101 illustrates the ignition and burning of the roof deck. Figure 102 provides a view of the array and roof assembly deflection. Figure 103 illustrates the roof and array prior to structural collapse. Figure 104 illustrates the test structure after collapse and suppression.

Figure 101 Open flames on roof

Figure 102 Modules sagging

Figure 103 Roof and modules collapsing

Figure 104 Roof collapsed -fire extinguished

Figure 105 provides a graph of the compartment interior temperatures – North thermocouple tree. Figure 106 provides a graph of the compartment interior temperatures – South thermocouple tree

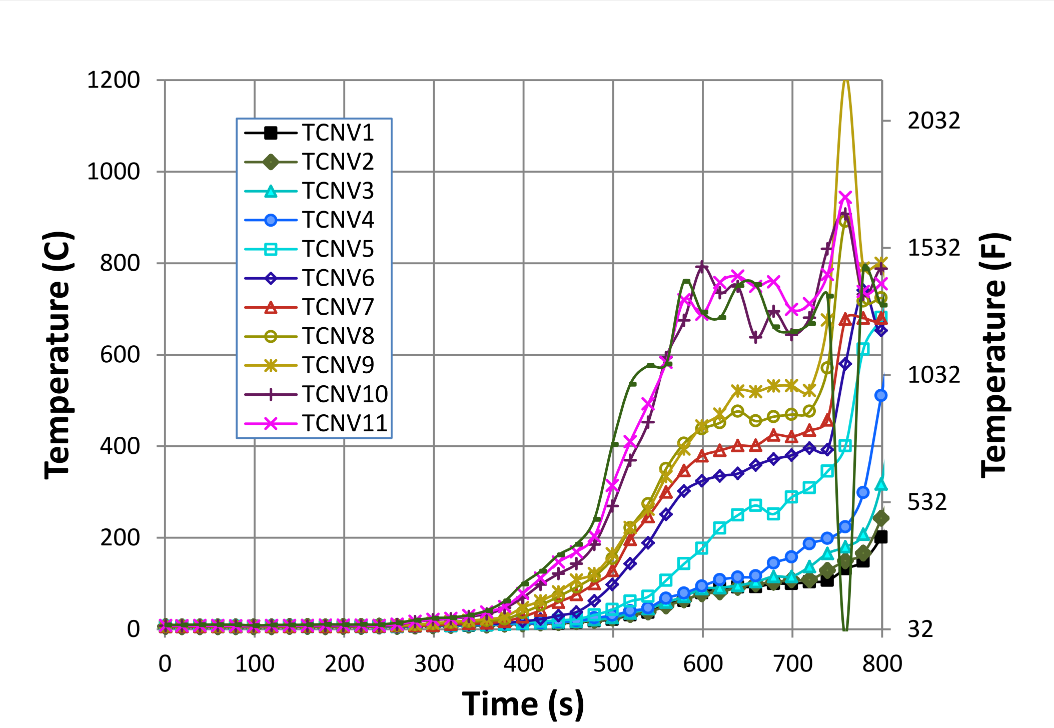

Figure 105 Compartment temperatures, north tree

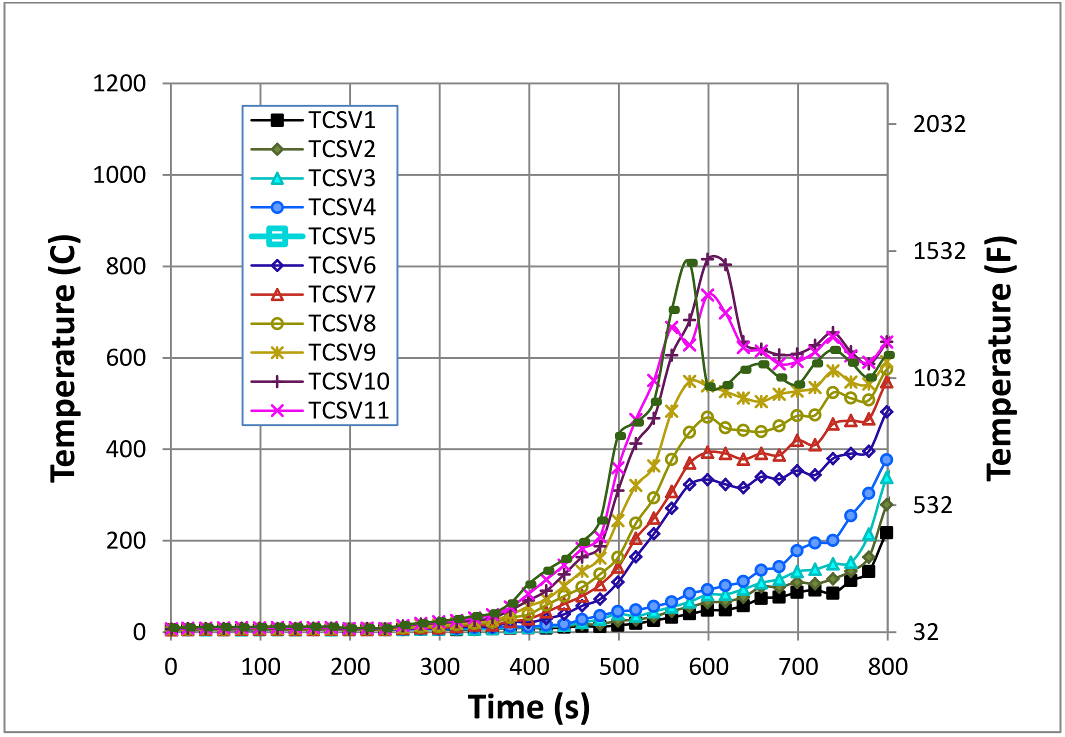

Figure 106 Compartment temperatures, south tree

Figure 107 provides a graph of the roof deck surface temperatures in the attic along the length of the roof. . Figure 108 provides a graph of the roof deck surface temperatures in the attic along the width of the roof.

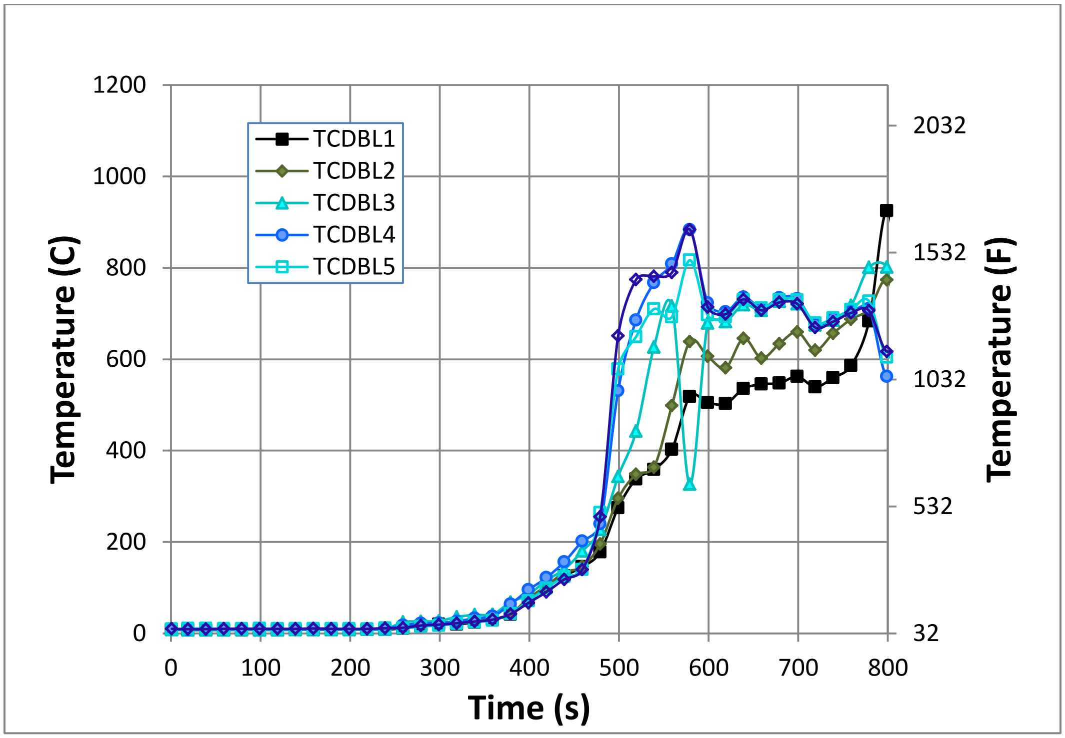

Figure 107 Centerline of roof deck surface (attic side) temperatures, length

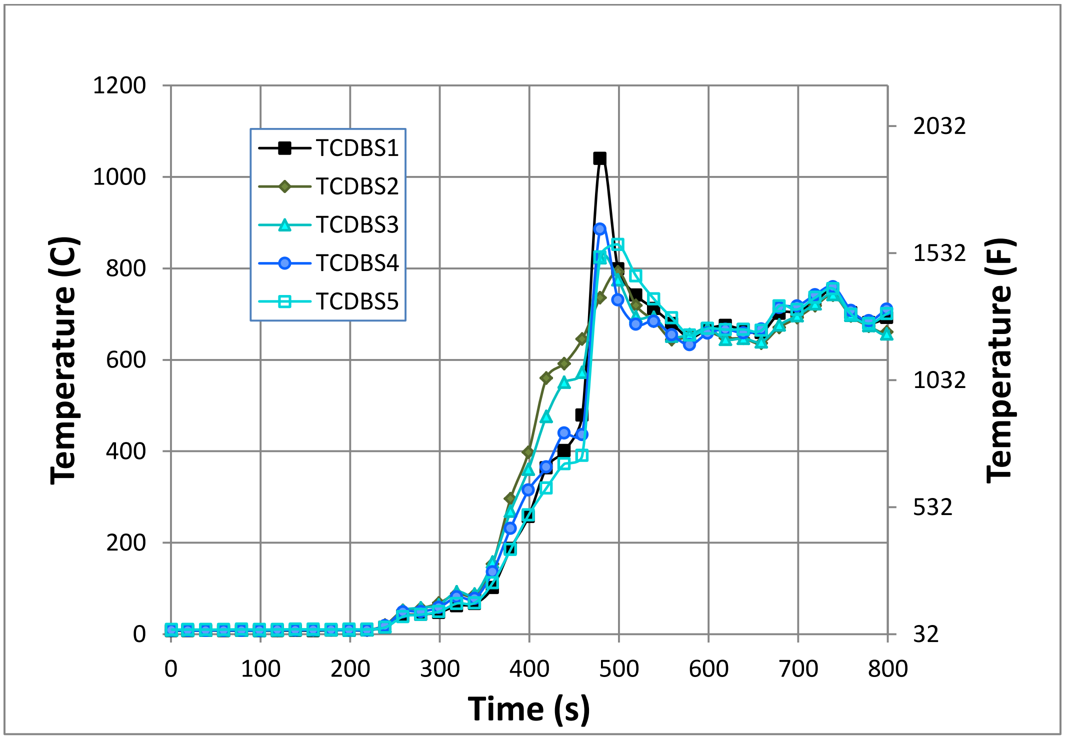

Figure 108 Centerline of roof deck surface (attic side) temperatures, width

Figure 109 provides a graph of the roof deck surface temperatures on the roof side along the length of the roof. Figure 110 provides a graph of the module back sheet temperatures the length of the roof. Figure 111 provides a graph of the module back sheet temperatures the width of the roof.

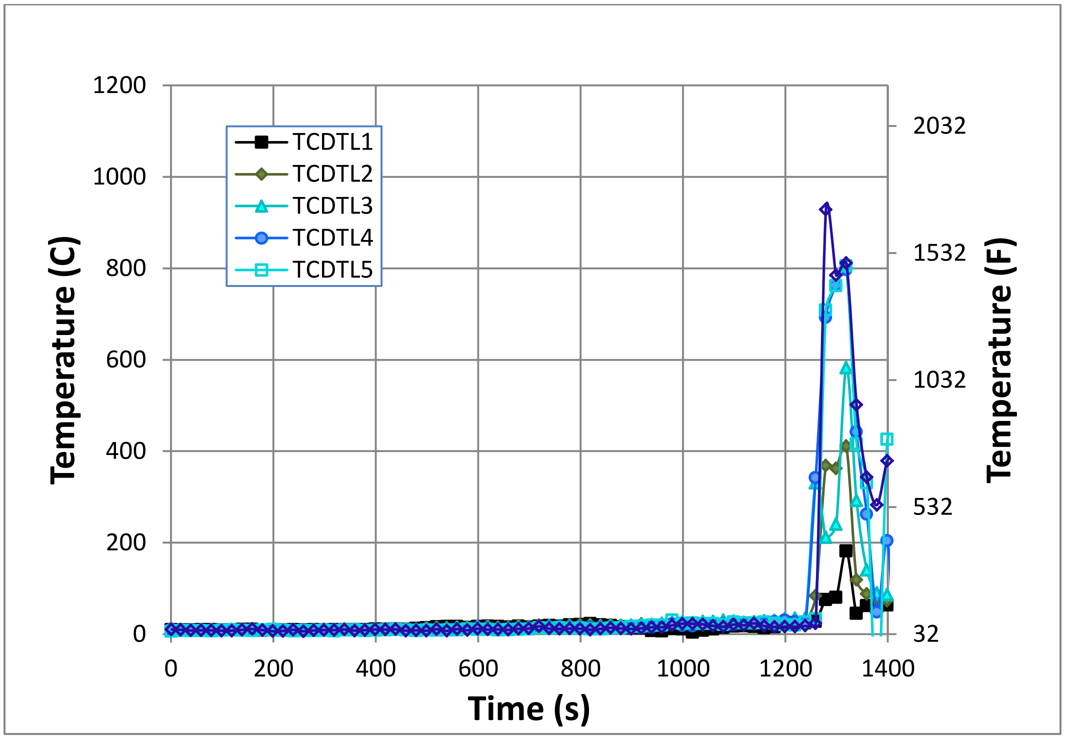

Figure 109 Centerline of roof deck surface (roof side) temperatures, length

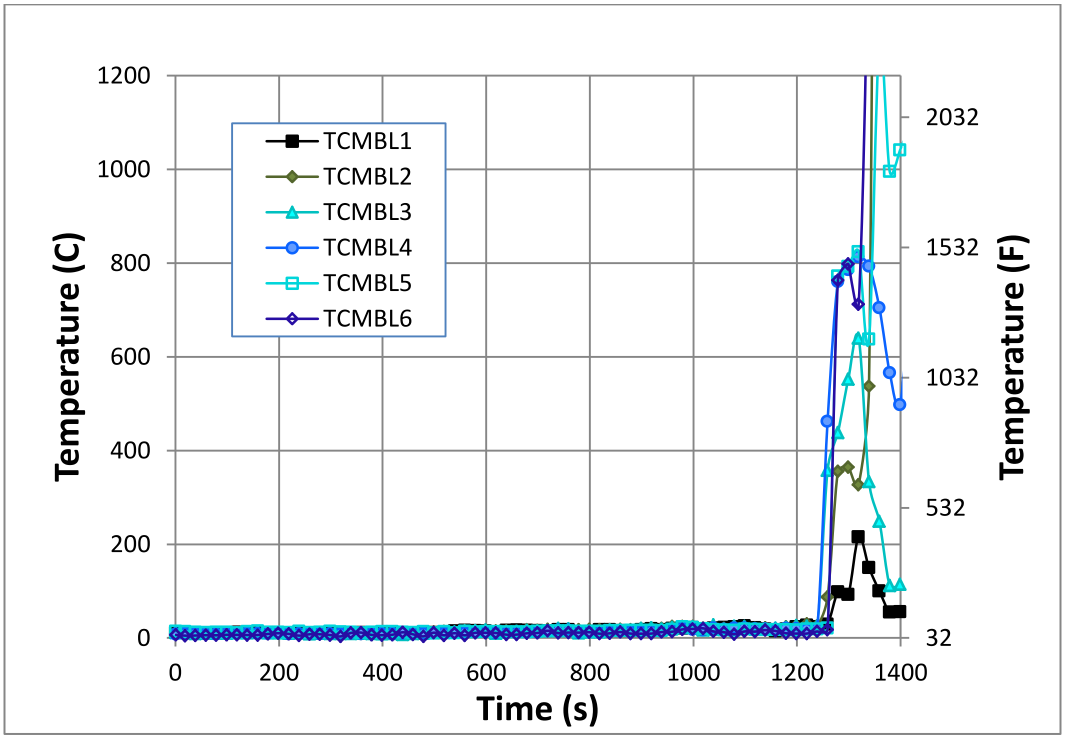

Figure 110 Module back plane temperatures, length

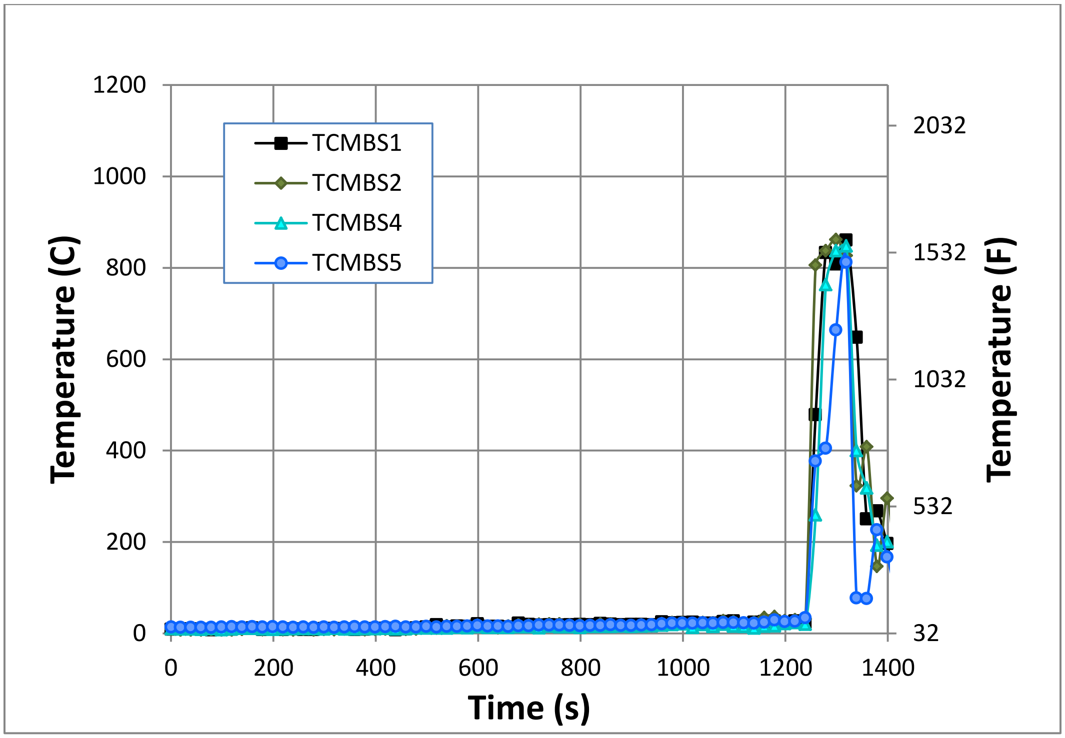

Figure 111 Module back plane temperatures, width

13.3.1. Post Fire Analysis - Glass on Polymer Metal Frame PV Modules

After the fire, each module was cut from the string, removed from the bunker, and placed in an open field where voltage and current measurements could be made in full sun. Modules E1, E2, F1, F2, and G1 were completely destroyed and producing no power. Modules A2, B1, and G2 had some damage and were producing less than full voltage. The remaining modules were fully functional and capable of producing full rated voltage and current. Figure 112 illustrates array damage. Figure 113 provides a view of the front of the array after the fire. Figure 114 provides a view of the back of the array after the fire.

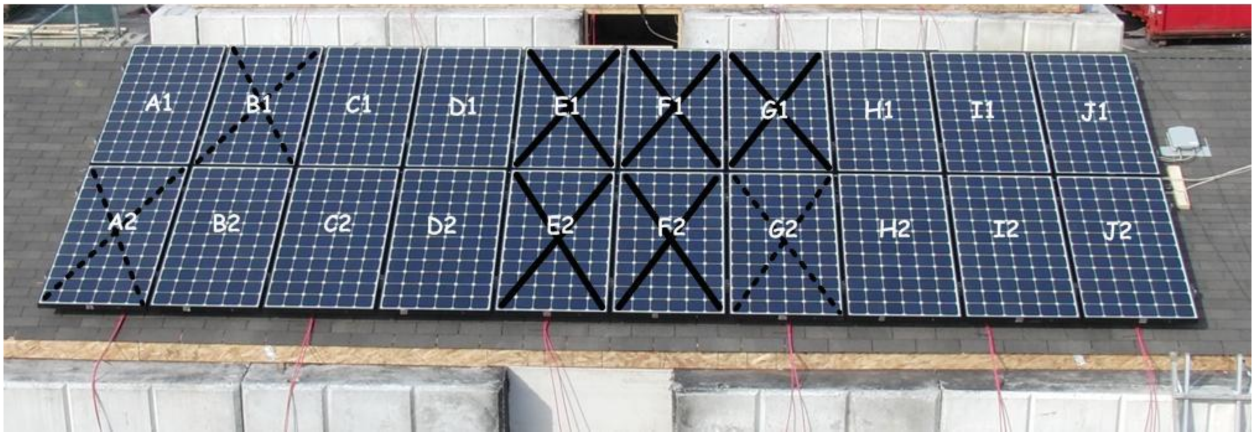

Figure 112 Roof diagram after fire: X = no power, dashed-X = partial power

Figure 113 Post fire, front surface

Figure 114 Post fire, back surface

Figure 115 through Figure 120 illustrate damaged but functioning modules.

Figure 115 Module A1 – damaged but functional and producing full voltage

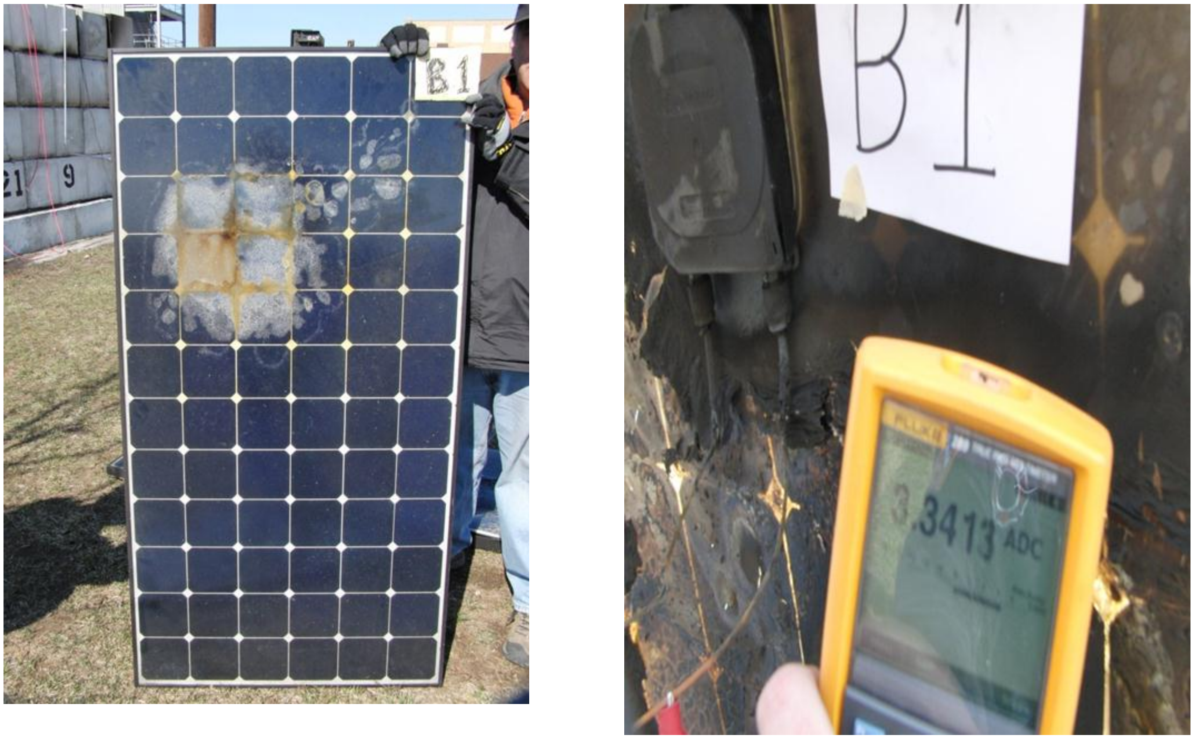

Figure 116 Module B1 – damaged but still producing over 3 amperes

Figure 117 - Module D1 – badly burnt on backside, but functional and producing full voltage

Figure 118 Module G2 – bottom portion of module glass and cells destroyed

Figure 119 Module G2 – still producing voltage and current

Figure 120 Module H1 – junction box burned, but still fully operational

13.3.2. Experiments with PV Laminate Modules

Experiments with PV laminate modules were conducted on March 4, 2011. The weather conditions at the time of the test were mostly sunny and 45 degrees F.

The fire load consisted of 20 wood pallets, stacked in two rows of 10 each. The wood pallets were located at ground level inside the bunker at the approximate center of the roof under the PV laminates. The total weight of the 20 wood pallets was 775 lbs.

The initial power conditions being produced by the PV array at the beginning of the test were 1000 watts, 368 volts DC, and 215 volts ac. The wood pallets were ignited with the standard UL igniter. The following observations were made as the fire test progressed:

After 2 minutes (elapsed time), the pallets were fully engulfed in flames, and by 4 minutes some smoke was observed at the bottom edge of the roof. After 6 minutes, the non-PV side of the roof appeared to be burning and smoking more than the PV (metal pan) side of the roof, and at 6 minutes 15 seconds the inverter turned off. At 8 minutes and 30 seconds, flames were observed at the front top peak of the gable end of the bunker. At 17 minutes some sag was observed in the cement board (non-PV) side of the roof, and at 19 minutes 30 seconds the roof and PV array collapsed into the building, and water was applied to extinguish the fire.

Figure 121 provides a view of the laminate / standing metal seam roof array. Figure 122 provides a view of the wood skid fuel package.

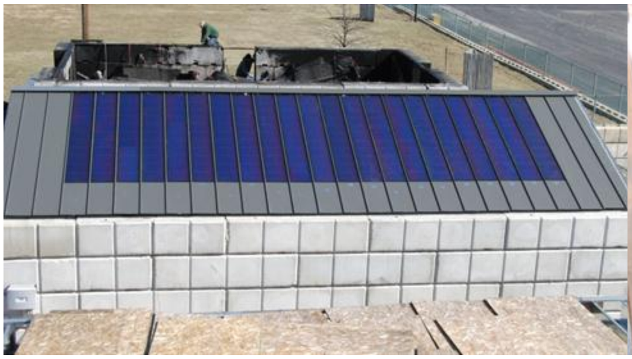

Figure 121 - Pre-Test conditions with laminates

Figure 122 Wood pallets ready for ignition

Figure 123 through Figure 126 illustrate increasing fire and smoke conditions during the experiment.


Figure 123 Smoke developing


Figure 124 Heavier smoke developing


Figure 125 - Flames developing


Figure 126 Roof and laminates collapsing

Figure 127 and Figure 128 provide a view of the condition of the PV laminate and metal roof after collapse of the structure.

Figure 127 Colapsed roof and laminates

Figure 128 Firefighters approaching Collapsed Laminates after Fire

Figure 129 provides a graph of the compartment interior temperatures – North thermocouple tree. Figure 130 provides a graph of the compartment interior temperatures – South thermocouple tree

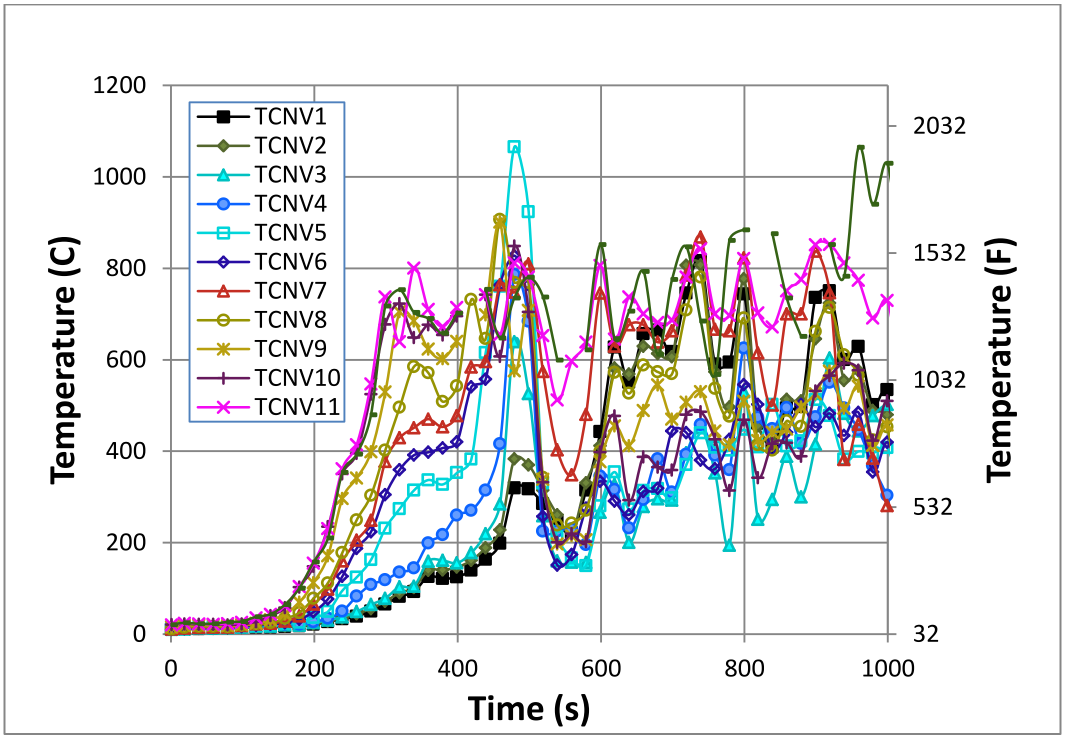

Figure 129 Compartment temperatures, north tree

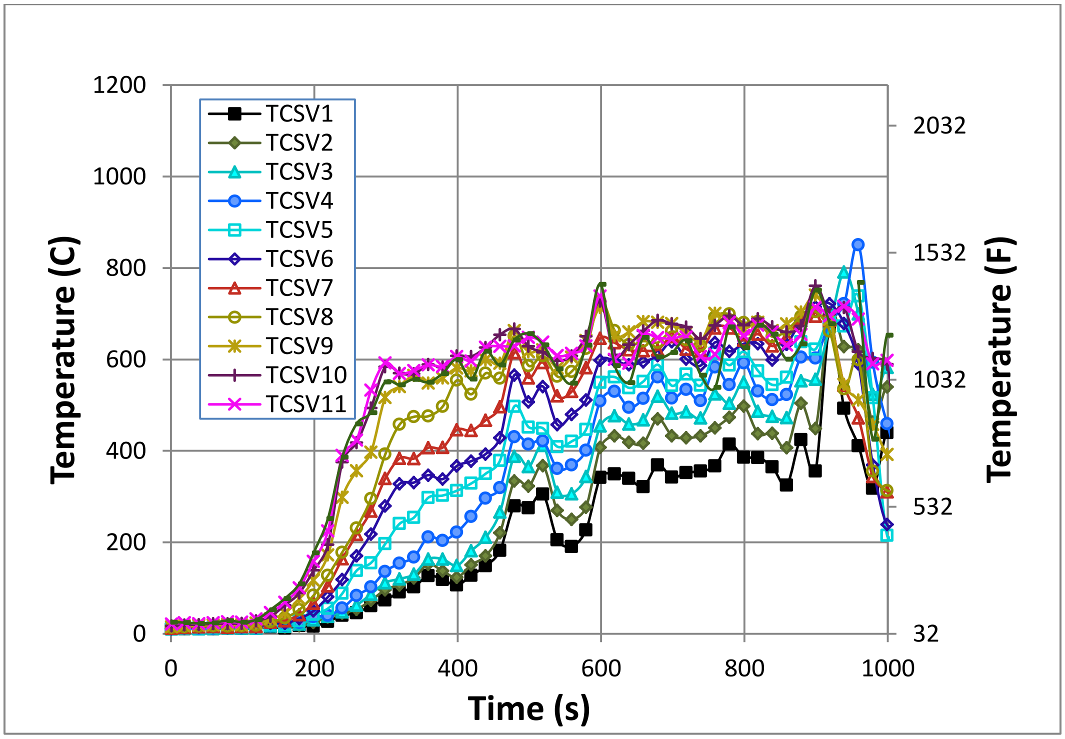

Figure 130 Compartment temperatures, south tree

Figure 131 provides a graph of the roof deck surface temperatures in the attic along the length of the roof. Figure 132 provides a graph of the roof deck surface temperatures in the attic along the width of the roof.

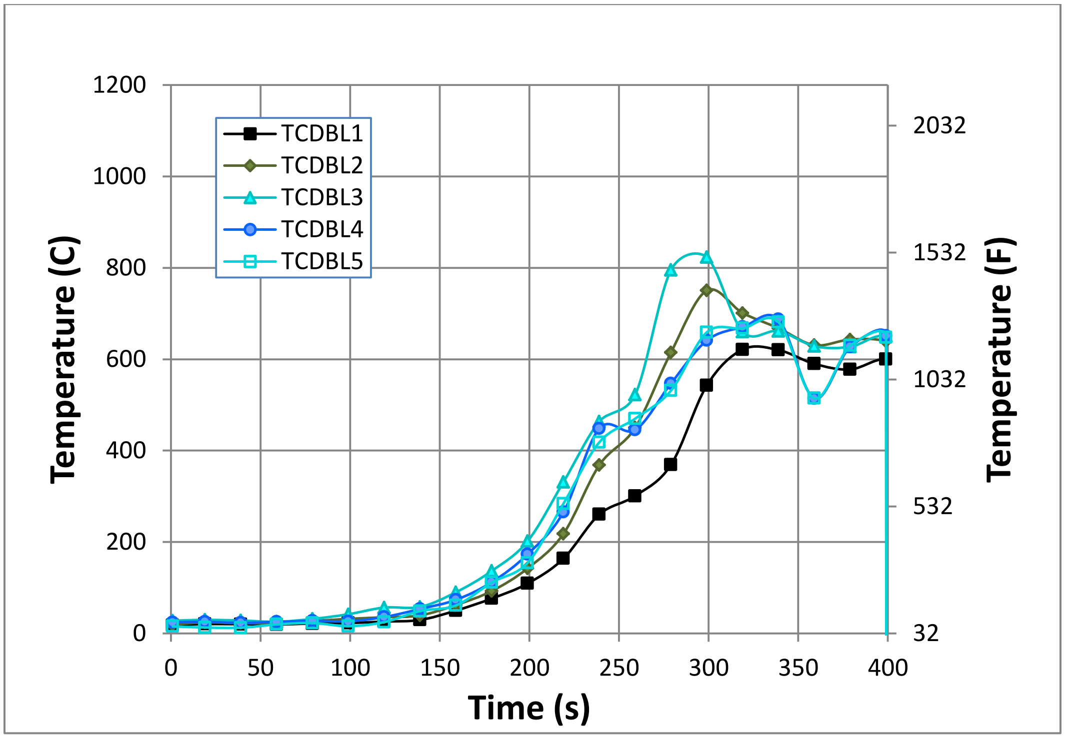

Figure 131 Centerline of roof deck surface (attic side) temperatures, length

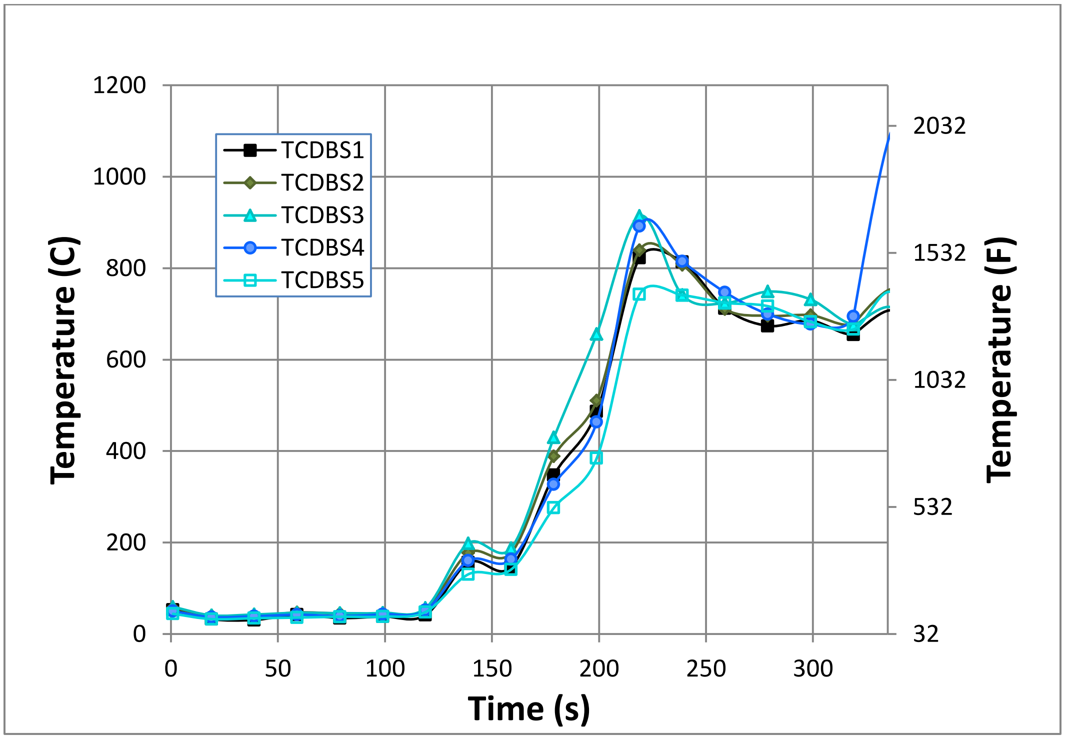

Figure 132 Centerline of roof deck surface (attic side) temperatures, width

Figure 133 provides a graph of the roof deck surface temperatures on the roof side along the length of the roof. Figure 134 provides a graph of the roof deck surface temperatures on the roof side along the width of the roof.

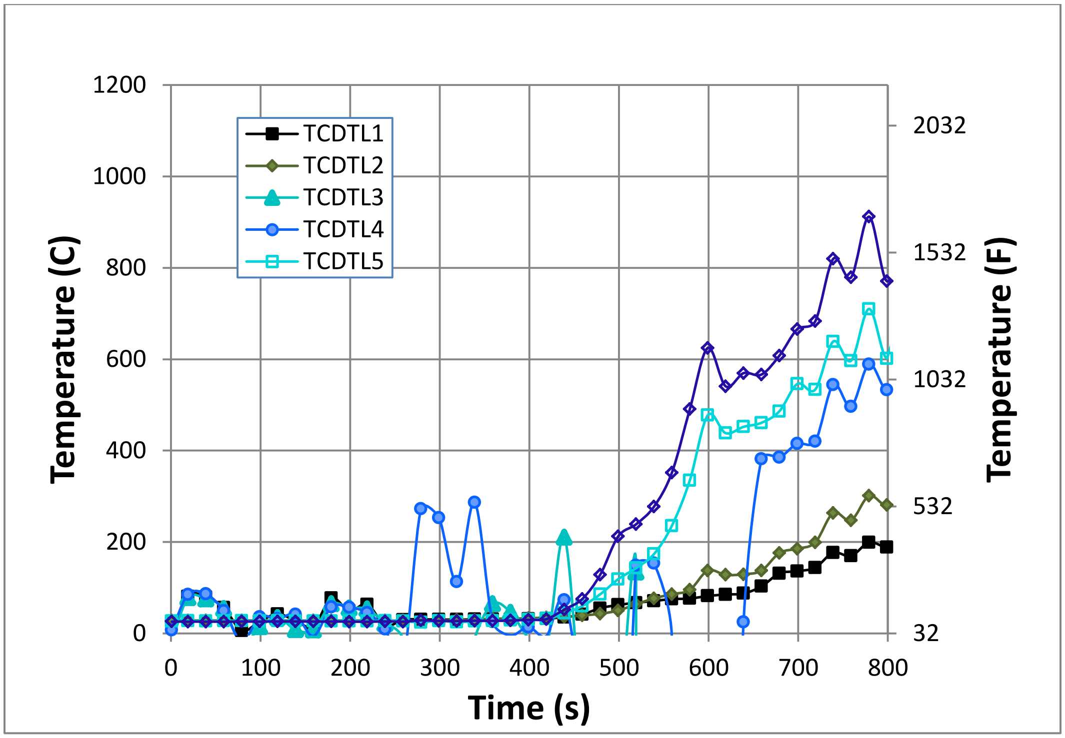

Figure 133 Centerline of roof deck surface (roof side) temperatures, length

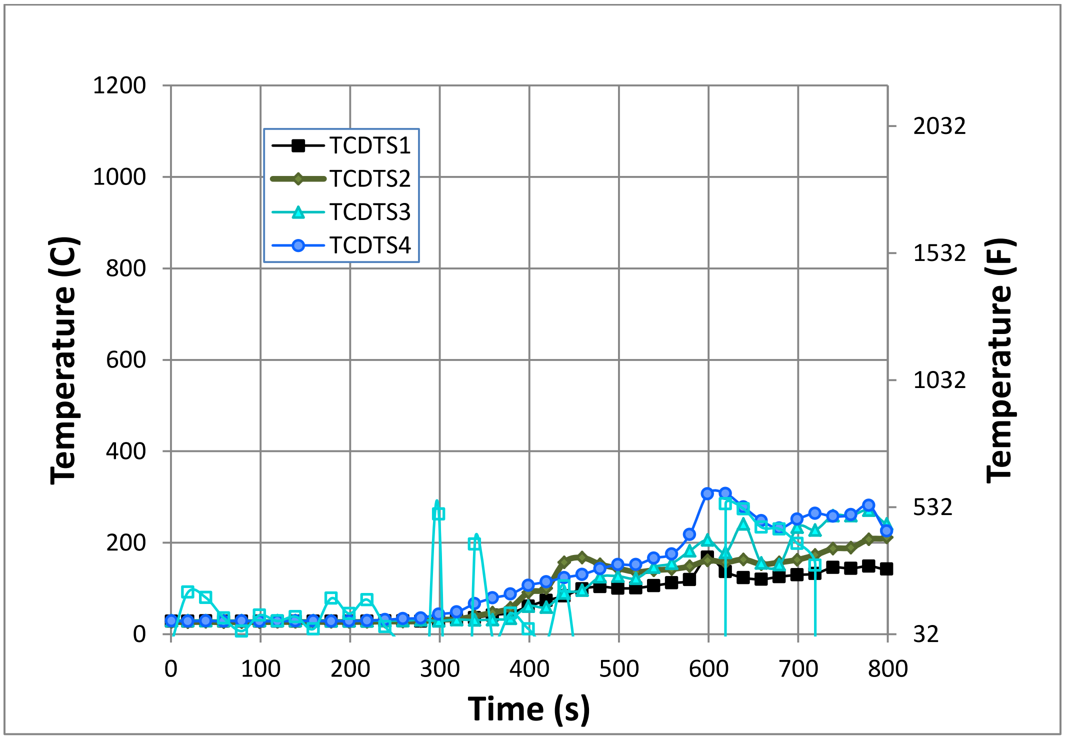

Figure 134 Centerline of roof deck surface (roof side) temperatures, width

13.3.3. Post Fire Analysis – Laminate Modules

After the fire, and while still in the collapsed position within the bunker, an examination and analysis of the damaged PV array was made. Only laminate numbers 1, 4, 17, 19, and 20 were able to measure any voltage as found after the fire while in that condition. A voltage of 3.5 volts was found on laminate #1 from an exposed lead pad at the junction box to the metal pan. Laminate numbers 4, 17, 19, and 20 measured 22 volts either between leads, or between a lead and the metal pan. There was typically a voltage potential from the positive lead of the laminate to the metal roof pans.

Figure 135 illustrates array damage.

Figure 135 Roof diagram after fire: X = no power

The laminates were then cut from the string, removed from the bunker, and placed in an open field were voltage and current measurements could be made in full sun. Laminates 7 through 13 were completely destroyed and producing no power. The remaining modules were fully functional and capable of producing full rated voltage and current.

Figure 136 through Figure 139 views of damage to the laminate including exposed wiring and bus..

Figure 136 Collapsed and damaged laminates

Figure 137 Exposed bare lead wires

Figure 138 Exposed bare wires at junction box

Figure 139 - Exposed bare live bus

Figure 140 illustrates voltage from damaged module.

Figure 140 Full voltage measured at damaged laminate

Figure 141 illustrates damage of the array.

Figure 141 Array reconstructed on ground, post-fire

13.3.4. Experiments with Solar Shingle Modules

The experiments with PV solar shingle modules were conducted on March 9, 2011. The weather conditions at the time of the test were mostly cloudy and 39 degrees F.

The fire load consisted of 20 wood pallets, stacked in two rows of 10 each. The wood pallets were located at ground level inside the bunker at the approximate center of the roof under the PV shingles. The total weight of the 20 wood pallets was 786 lbs.

The initial power conditions being produced by the PV array at the beginning of the test were 373 watts, 461 volts DC, and 208 volts ac. The wood pallets were ignited with the standard UL igniter. The following observations were made as the fire test progressed:

After 2 minutes (elapsed time), the pallets were fully engulfed in flames, and by 4 minutes some smoke was observed coming from the door and window areas, and by 5 minutes smoke was coming from the eves. After 6 minutes, there was some burning observed on the roof and smoke coming from between the shingles. At 8 minutes there was open flame coming from the back of the bunker, and by 10 minutes the roof structure was on fire with the plastic shingles beginning to deform. At 15 minutes the roof was in flames, and at 16 minutes the ground-fault detection and interruption fuse within the inverter opened and the inverter turned off. At 17 minutes 30 seconds the center of the roof caved in, although the roof deck did not collapse to the ground. At 18 minutes water was applied to the fire and the test was terminated. After the fire was extinguished, the roof deck was purposely collapsed to ground to facilitate examination and recovery of the shingles.

Figure 142 provides a view of the PV shingle array prior to the experiment. Figure 143 illustrates the burning of wood skid fuel package.

Figure 142 Pre-test conditions with shingles

Figure 143 Wood pallets engulfed in flames

Figure 144 through Figure 147 illustrate the developing smoke and fire conditions prior to structural collapse.

Figure 144 Smoke rising from roof

Figure 145 Flames from backside of roof

Figure 146 Solar shingles on fire

Figure 147 Roof beginning to collapse

Figure 148 illustrates suppression of the partially collapsed roof.

Figure 148 - Partial collapsed roof during extinguishment

Figure 149 provides a graph of the compartment interior temperatures – North thermocouple tree. Figure 150 provides a graph of the compartment interior temperatures – South thermocouple tree

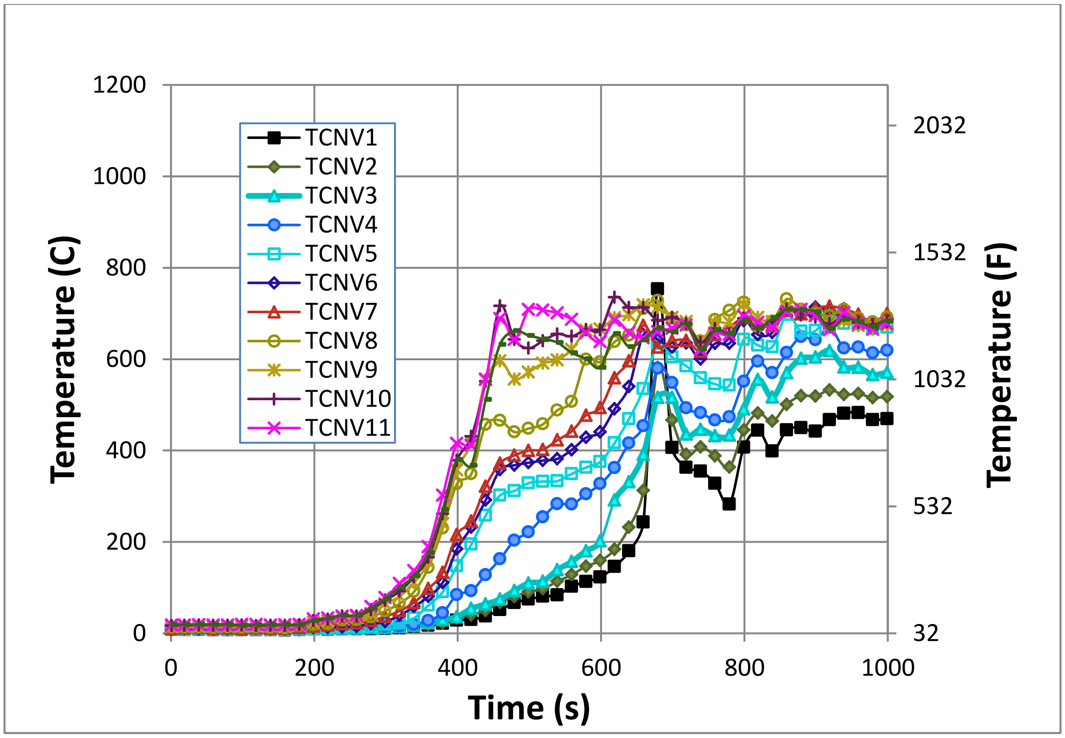

Figure 149 Compartment temperatures, north tree

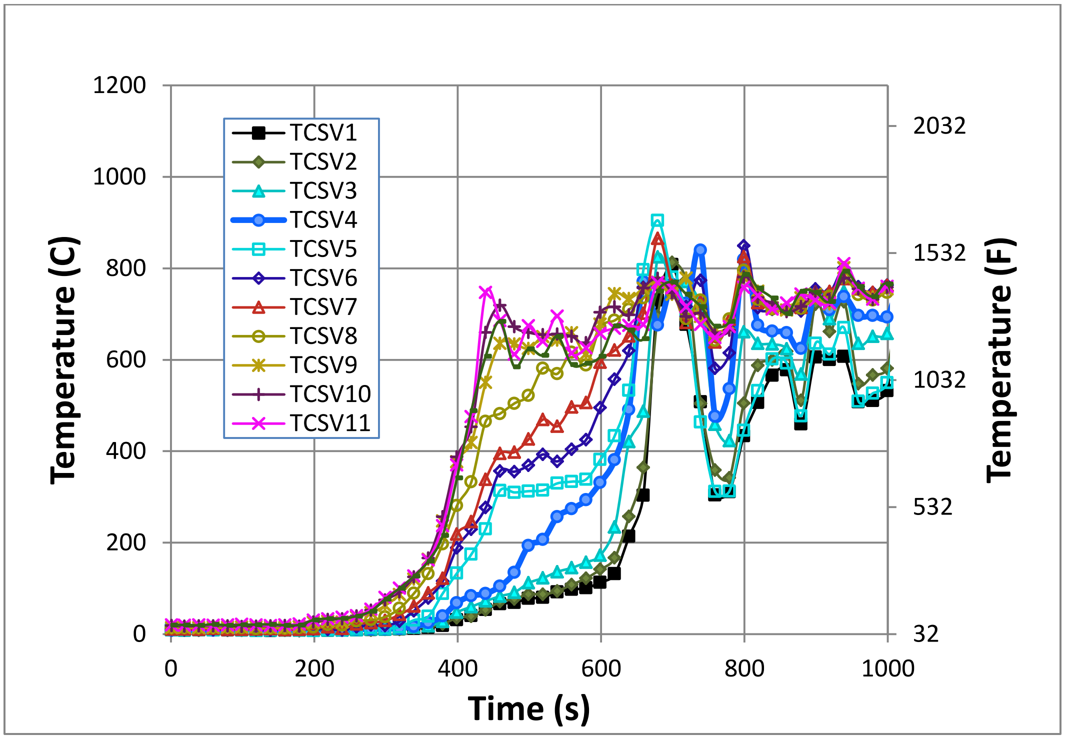

Figure 150 Compartment temperatures, south tree

Figure 151 provides a graph of the roof deck surface temperatures in the attic along the length of the roof. Figure 152 provides a graph of the roof deck surface temperatures in the attic along the width of the roof.

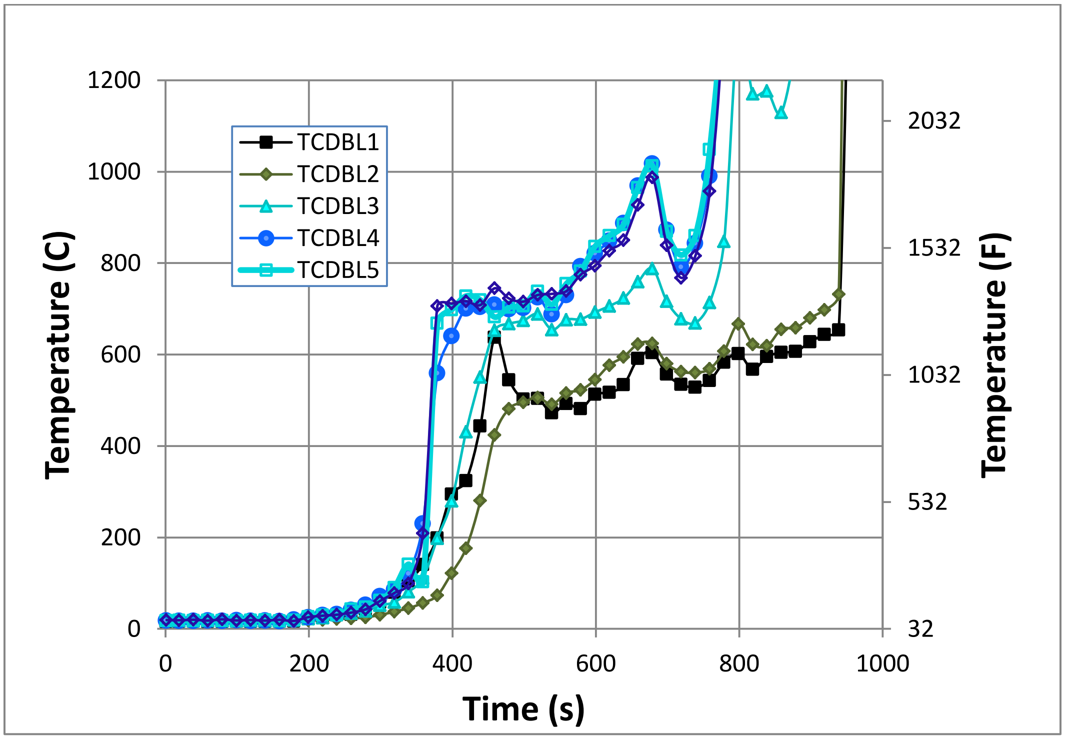

Figure 151 Centerline of roof deck surface (attic side) temperatures, length

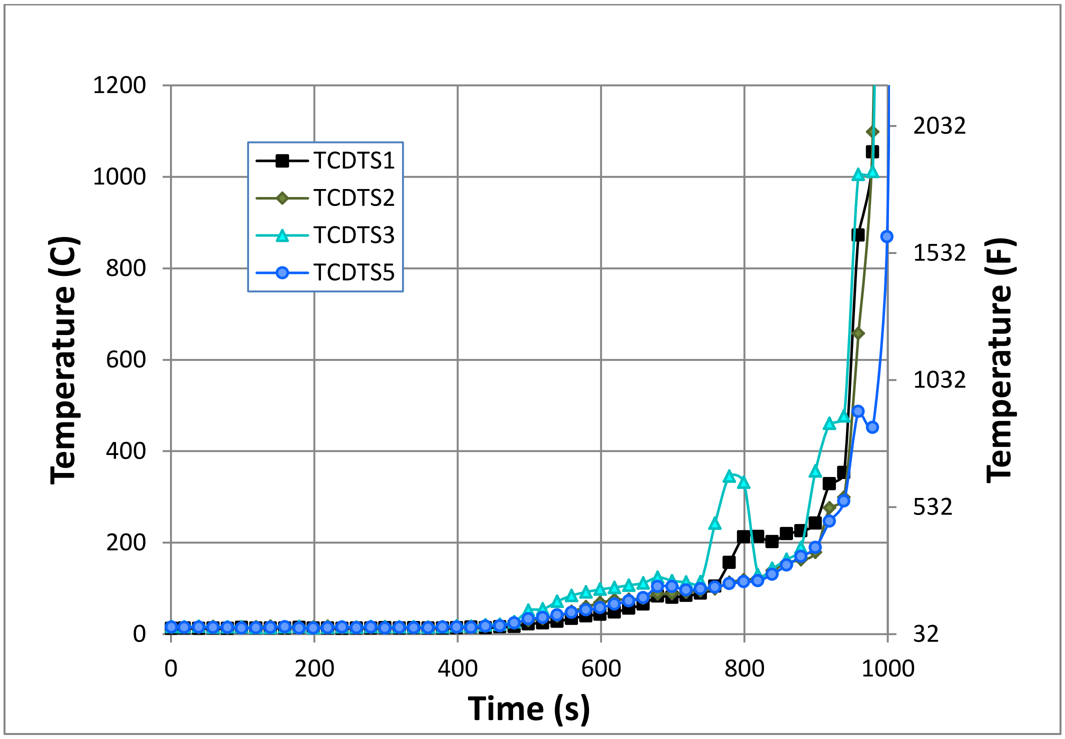

Figure 152 Centerline of roof deck surface (attic side) temperatures, width

Figure 153 provides a graph of the roof deck surface temperatures on the roof side along the length of the roof.   Figure 154 provides a graph of the module back sheet temperatures the length of the roof.

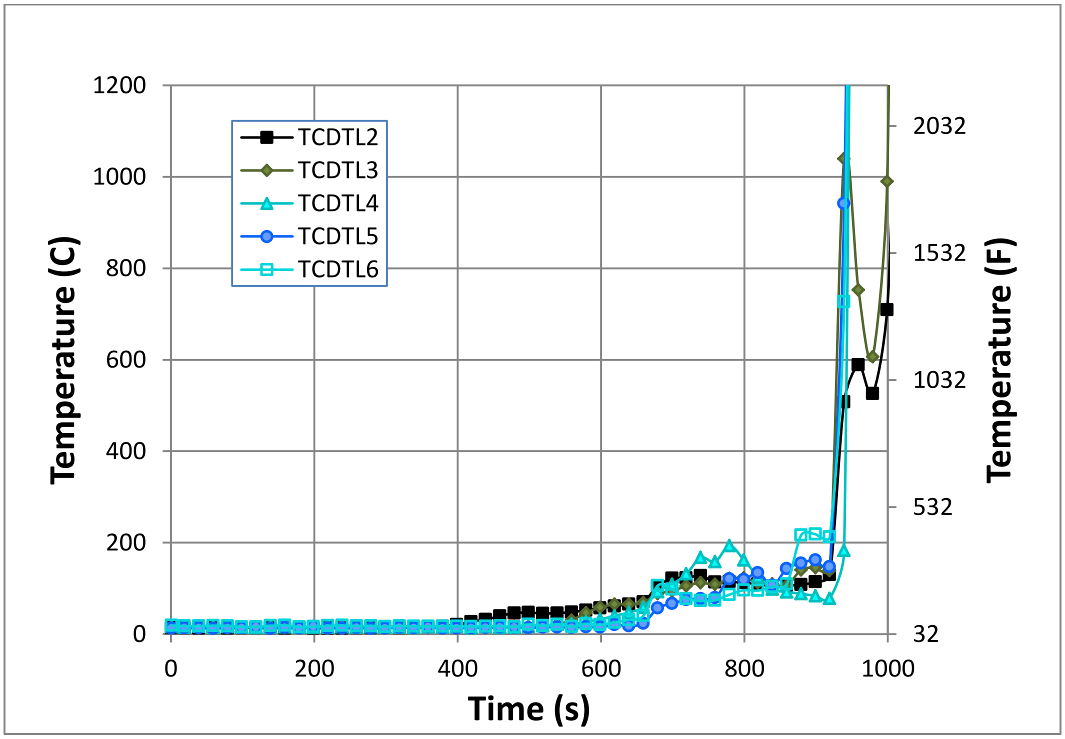

Figure 153 Centerline of roof deck surface (roof side) temperatures, length

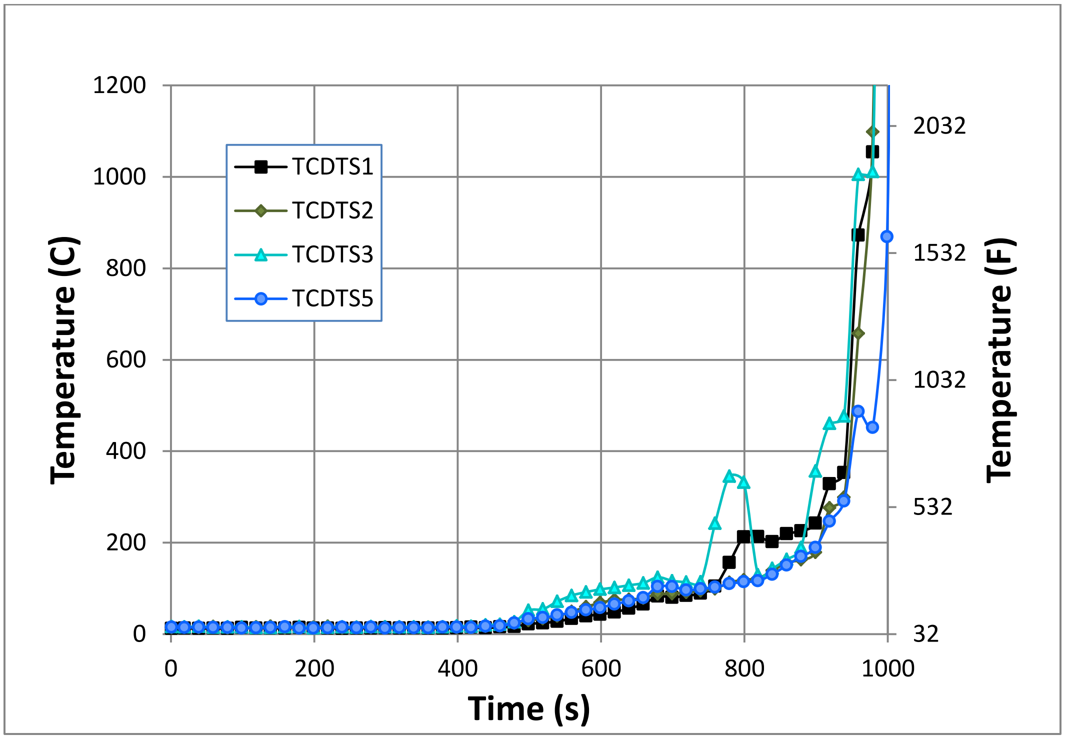

Figure 154 Centerline of roof deck surface (roof side) temperatures, width

13.3.5. Post Fire Analysis – Solar Shingle Modules

After the fire, and while still in the collapsed position within the bunker, an examination and analysis of the damaged PV array was made. The "home run" was found exposed with most of the conductor insulation burned off. 47 volts open circuit and 150 milliamps short circuit was measured between the bare home run and shingle G2 within the rubble.

The shingles were then cut from the string, removed from the bunker, and placed in an open field were voltage and current measurements could be made in full sun. Shingles B1, C1 – C8, D1 – D8, E1 – E8, F1 – F8, G4, and G8 were destroyed and producing no power. The remaining shingles were fully functional and capable of producing full rated voltage and current. However, many of these functional modules were badly burned exposing live copper bus and bare conductors. See Figures 5.8.10.2 and 5.8.10.5.

Figure 155 illustrates array damage. Figure 156 and Figure 157 illustrate exposed conductors and voltage from a damaged module.

Figure 155 Roof diagram after fire test: “X” or “–” represents no power

Figure 156 Exposed lead conductors in rubble

Figure 157 Voltage between exposed wires

Figure 158 provides a view of the array after the experiment.

Figure 158 Array reconstructed on ground, post-fire

Figure 159 and Figure 160 provide a view of a damaged module which continued to generate power.

Figure 159 Shingle B7 with exposed lead conductor

Figure 160 Damaged shingle G8, exposed conductors and bus - fully functional

13.4. Additional Experiments with Roof Rail Mounted Metal-Frame Modules

After the initial experiments with modules of the glass on polymer metal frame, laminate, and solar shingle types, some additional experiments were planned using the fire test array construction with metal-frame modules to explore 1) a confined fire directed from inside the bunker to the roof through a window, and 2) fire originating on the roof from material and debris located under the modules. These additional experiments were also designed to terminate the fire before the roof collapsed, thus presenting challenges in conducting overhaul operations with a partially damaged, but potentially electrically hazardous roof array.

13.4.1. Confined Fire Directed Toward Roof

For this experiment, the bunker with modules on an aluminum rail mounting system was reconstructed similar to the previous test with metal-frame modules. This involved a test array consisting of 20 modules, with two parallel strings of 10 modules wired in series.

The fire load consisted of 20 wood pallets, stacked in two rows of 10 each. The wood pallets were located at ground level inside the bunker at the approximate center of the roof under the PV modules and adjacent to an opening, to represent a window, located on the east side of the bunker. These wood pallets were positioned in a small compartment within the bunker that was sheathed with cement board on all sides to help confine the fire to that space and force the fire to vent out through the adjacent window. In addition, the compartment ceiling prevented fire spread into the attic and protected the wood truss construction. The total weight of the 20 wood pallets was 795 lbs.

Figure 161 illustrates the fuel package within the gypsum

Figure 161 Photograph of wood skid fuel package in room.

This first experiment was conducted on April 20, 2011. The weather conditions at the time of the test were mostly cloudy, and the solar irradiance was approximately 385 W/m^2 incident to the roof. The initial power conditions being produced by the PV array at the beginning of the test were 1750 watts, 404 volts DC, and 217 volts ac. The wood pallets were ignited using the standard UL igniter. The following observations were made as the fire test progressed:

After 6 minutes, flames approximated 4 – 5 feet long were shooting from the window opening, and this progressed to about 8 – 10 foot flames by 8 minutes. Due to local weather conditions, only a slight wind was coming from the east, and thus the flames were only able to produce a slight ignition of the roof, which subsided as the wood pallets burned-out. After 19 minutes, the fire had mostly stopped, and water was applied. There was only slight damage to the bottom edge of the lower two modules directly over the window opening.

This test was repeated the following day under similar conditions, but with the addition a fire department ventilation fan in an attempt to direct air towards the window opening. The ambient wind conditions at the time of the test was with varying wind direction conditions of approximately 200 feet per minute toward the test structure. With the fan,the air velocity was measured to be approximately 500 feet per minute at the roofline. However, the fan did not overcome the local wind conditions and the experiment was terminated after 18 minutes.
Figure 162 provides a view of the window vent from the compartment. Figure 163 through Figure 166 illustrate the fire existing the window vent.

Figure 162 Confined ignition space in bunker

Figure 163 Flames forced out window opening

Figure 164 Flames propagate out window

Figure 165 Fire terminated

Figure 166 Fan used to help force flames towards roof

Figure 167 provides a graph of the compartment interior temperatures**.**

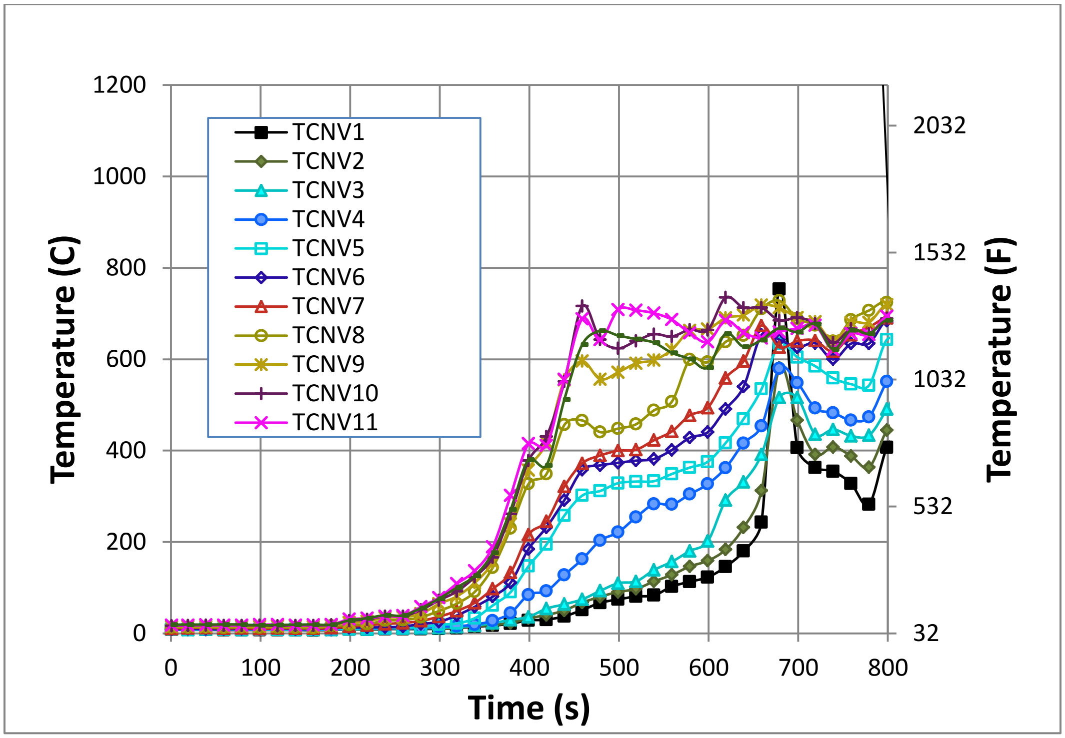

Figure 167 Compartment Temperatures

Figure 168 provides a graph of the roof deck surface temperatures in the attic along the length of the roof. Figure 169 provides a graph of the roof deck surface temperatures in the attic along the width of the roof.

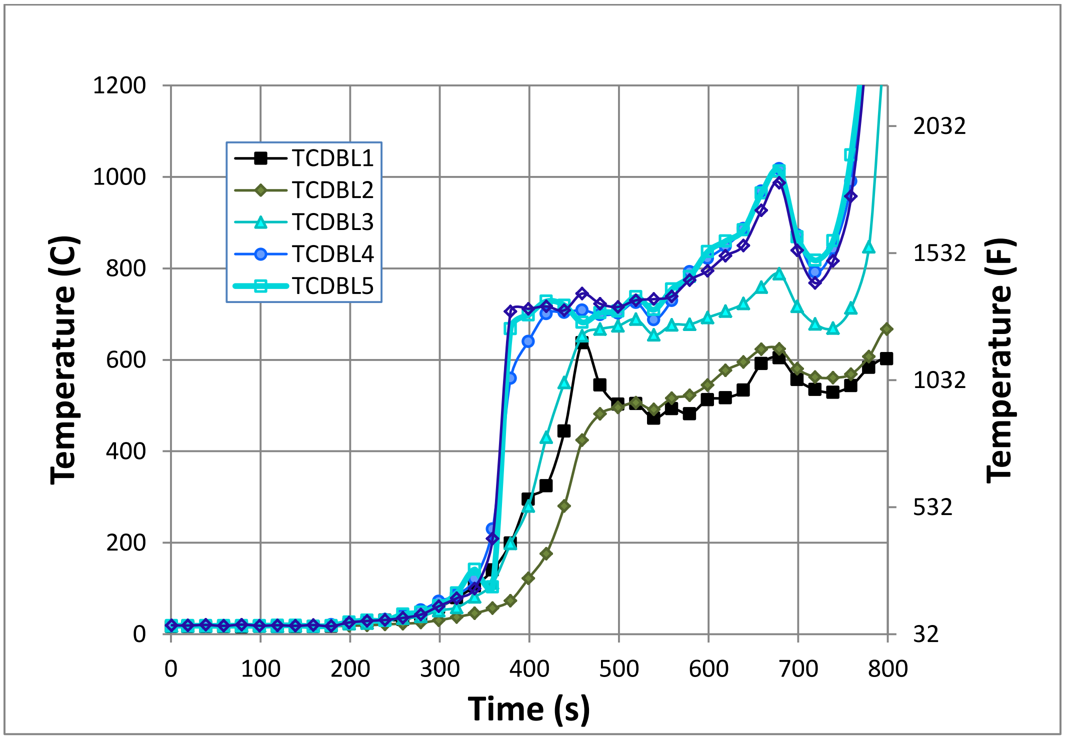

Figure 168 Centerline of roof deck surface (attic side) temperatures, length

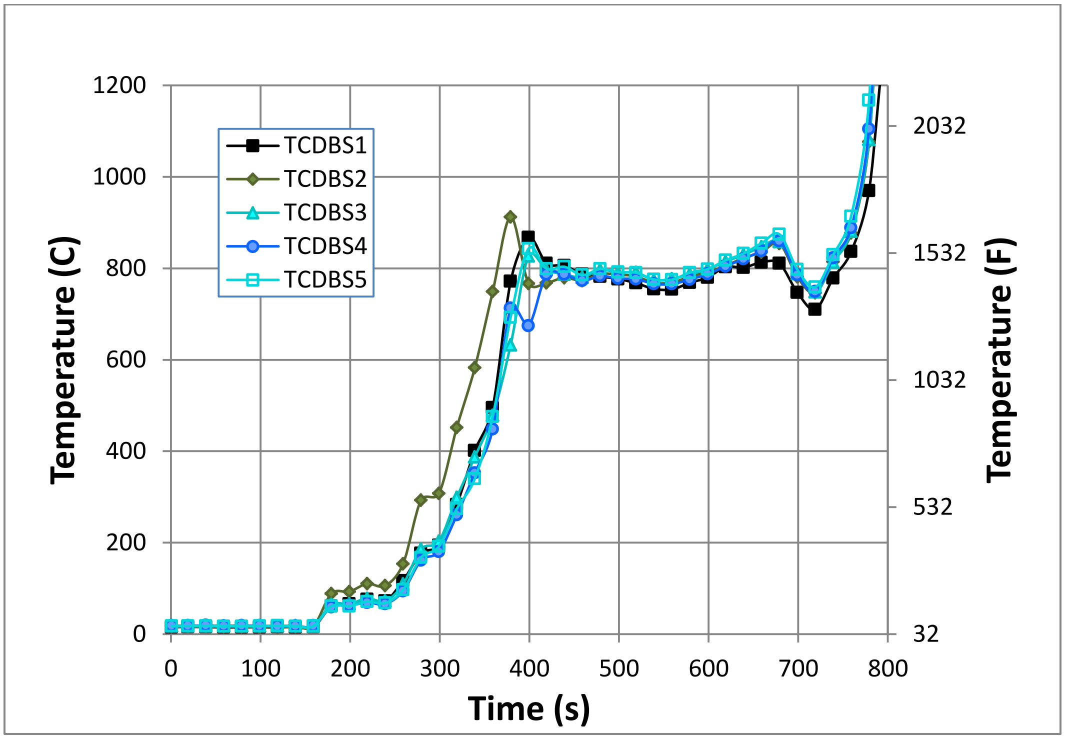

Figure 169 Centerline of roof deck surface (attic side) temperatures, width

Figure 170 provides a graph of the roof deck surface temperatures (exterior) along the length of the roof.

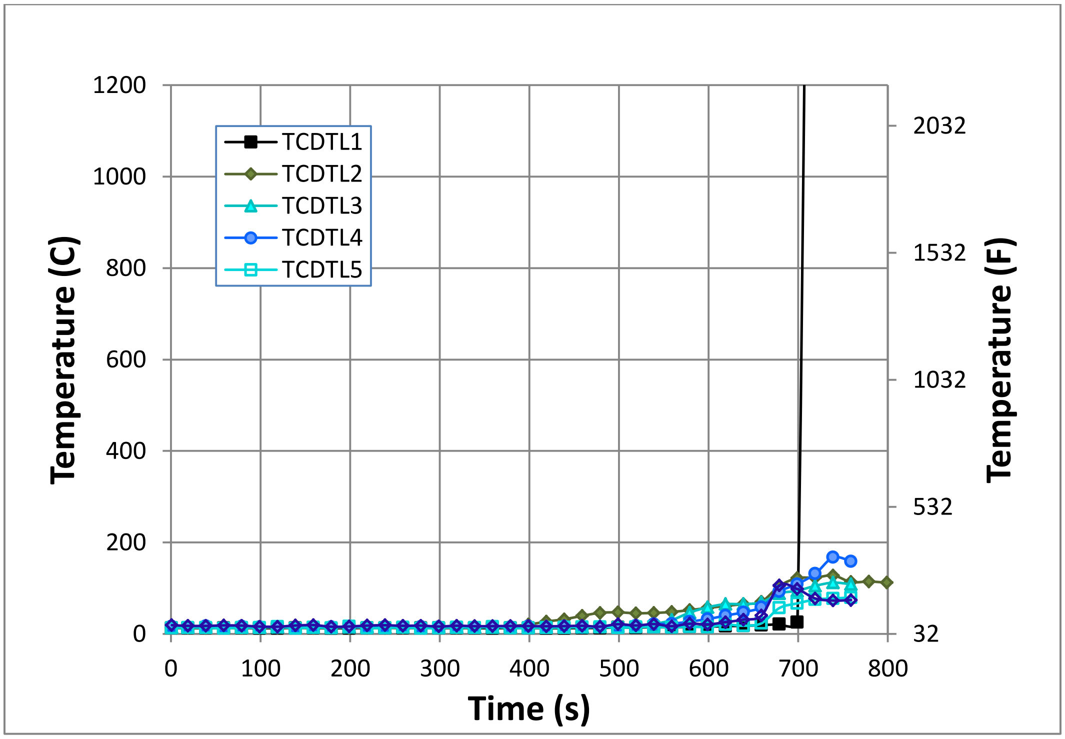

Figure 170 Centerline of roof deck surface (roof side) temperatures, length

13.4.2. Roof Fire 1 Started Under Modules (A2 & A3)

For this experiment, the bunker with modules on an aluminum rail mounting system was reconstructed similar to the previous test with modules. This involved a test array consisting of 20 modules, with two parallel strings of 10 modules wired in series.

The fire load consisted placing 3.2 lbs. (1455 grams) of pine straw plus a “B” brand directly under modules E2 and F2 (center of bottom string of array).

This first experiment with a roof fire was conducted on April 20, 2011. The weather conditions at the time of the test were partly cloudy, and the solar irradiance was approximately 710 W/m^2 incident to the roof. The wind was approximately 300 – 500 feet per minute, with gusts up to 700 feet per minute out of the west to southwest. The array was facing east. The initial power conditions being produced by the PV array at the beginning of the test were 2740 watts, 395 volts DC, and 223 volts ac. The pine straw and B-brand were ignited with a propane torch. The following observations were made as the fire test progressed:

The test was only producing a light smoke, with some flame under the modules, especially when the wind picked-up. The test was stopped after 48 minutes, as there was no visible flame on the roof or inside the bunker. There was only some visible damage to the glass of modules E2 and F2.

The test was continued by placing and igniting an “A Brand” under module D2. After 6 minutes into this continuation of the test, open flames were observed and module D2 began to sag. By 12 minutes, vertical flames were observed along the complete length of module D2. At 13 minutes, there was heavy smoke and flames, and module D2 had completely sagged in, and at 14 minutes the inverter turned off, with the array voltage still over 300 volts. For the next several minutes flames were noticed between modules C2 and D2, and flames also at the top peak of the roof at modules D1 and E1. At 21 minutes the test was terminated, and water was applied. The array voltage was about 230 volts at the end of the test. There was no structural damage to the roof.

Figure 171 and Figure 172 illustrate the roofing brand and pine straw fuel package positioned under the array and ignited.

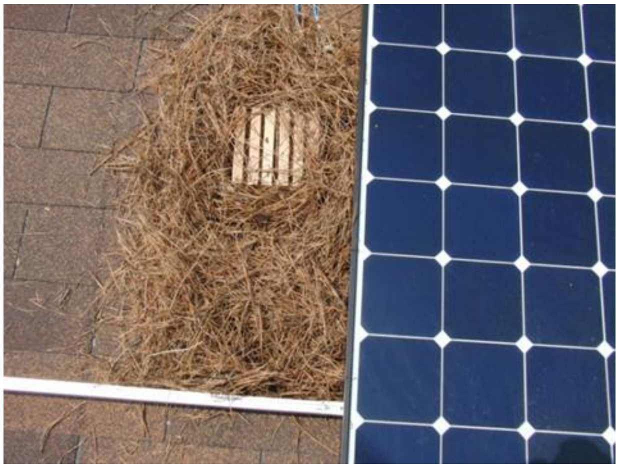

Figure 171 Pine straw and brand under module

Figure 172 Igniting pine straw

Figure 173 through Figure 175 illustrate the fire spread under the array extending up to the roof peak. Figure 176 illustrates suppression of the roof and PV modules.

Figure 173 Fire propagating under modules

Figure 174 Flames spreading

Figure 175 Modules sagging from heat

Figure 176 Fire being extinguished

Figure 177 provides a view of the damage to the array.

Figure 177 Firefighters assessing damage after fire

Figure 178 provides a graph of the roof deck surface temperatures on the roof side along the length of the roof. Figure 179 provides a graph of the roof deck surface temperatures on the roof side along the width of the roof. Figure 180 provides a graph of the back plane surface of the PV modules along the length of the roof.

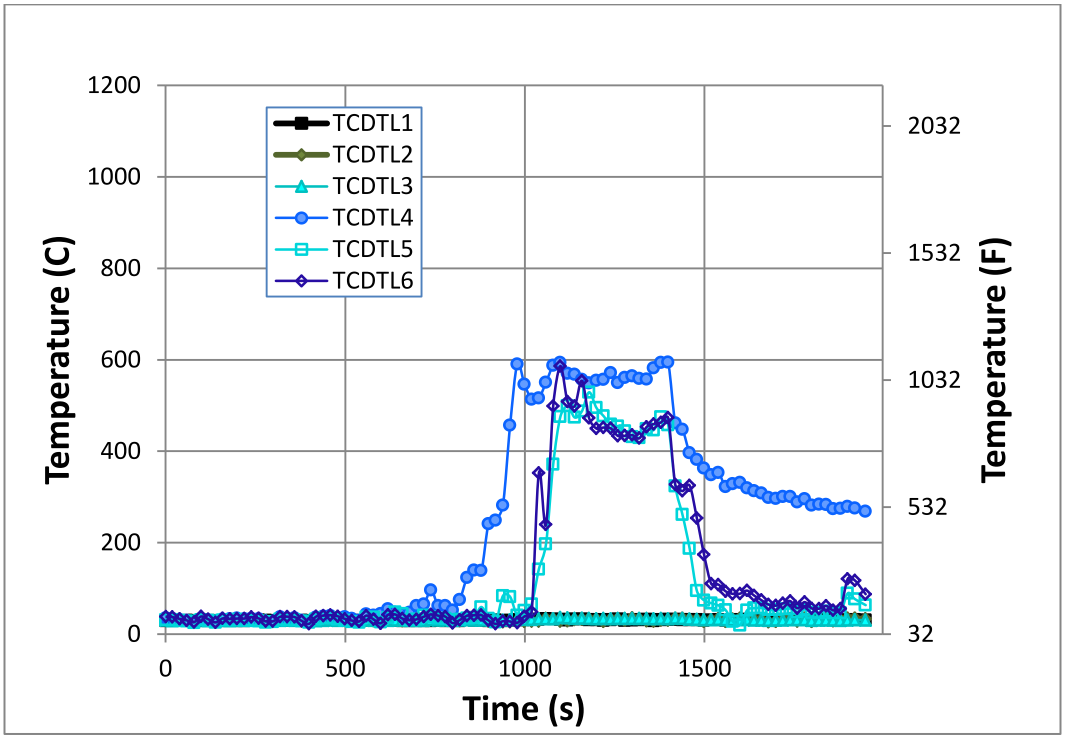

Figure 178 Centerline of roof deck surface (roof side) temperatures, length

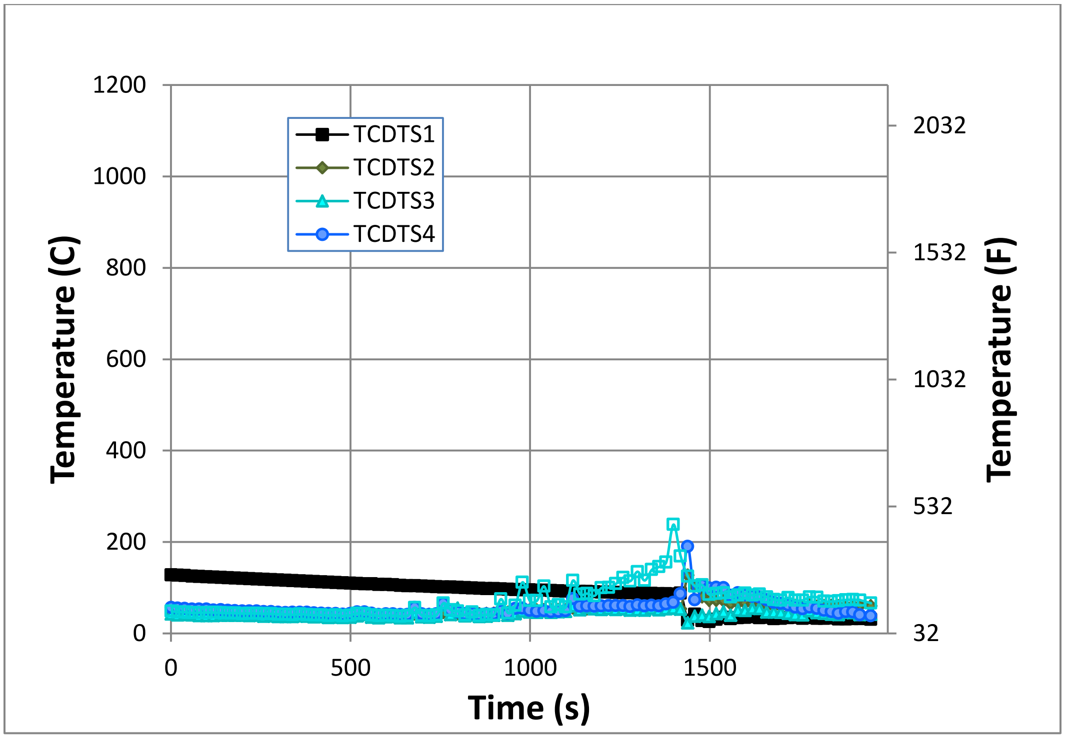

Figure 179 Centerline of roof deck surface (roof side) temperatures, width

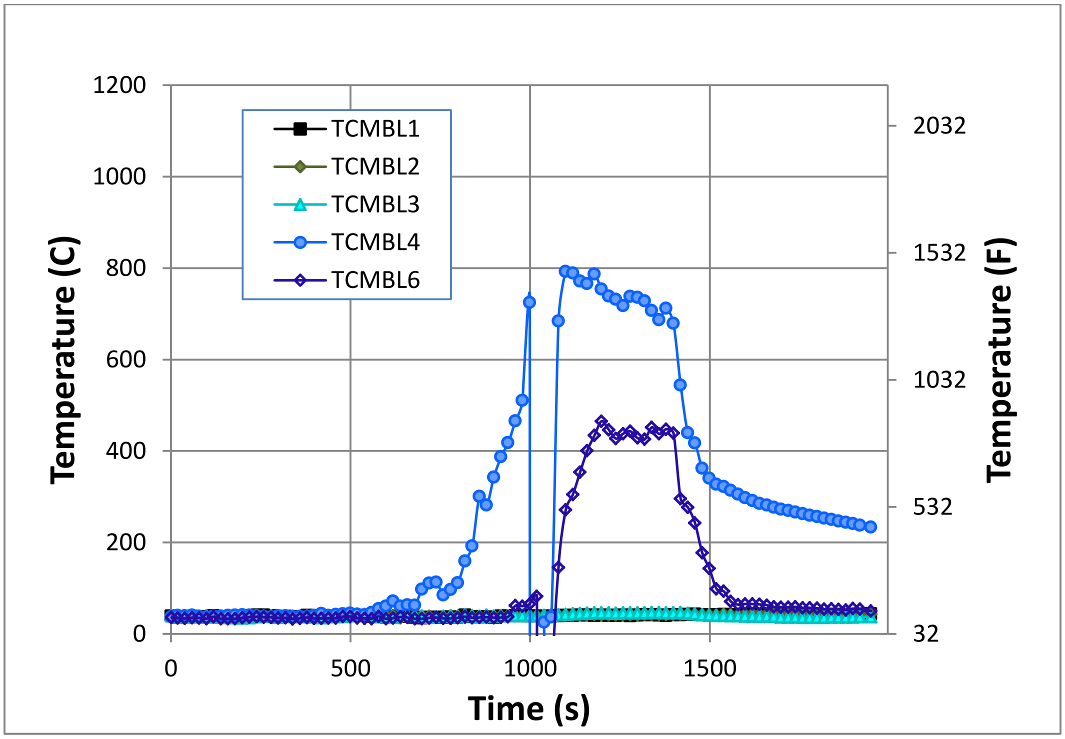

Figure 180 Centerline of PV module temperatures, length

13.4.3. Post Fire Analysis - Roof Fire 1 Started Under Modules

With the assistance of the professional PV installation contractor, the situation of the fire damaged PV array was analyzed to determine if hazardous energy was still present, and how the array could be safely disassembled and removed from the roof to ground. From general observations of the array, modules C1, D1, C2, D2 and E1 were heavily damaged. Since there were voltage sense leads attached to the modules for test purposes, it was easy to determine that most of the remaining modules had full voltage. It should be noted that in a real fire situation, this would not be as easy to determine. Also, it was observed that the fire had damaged the wire insulation to many of the conductors, and also had melted the aluminum mounting rail in several places, thus possibly losing ground continuity.

Disassembling the array after the fire presented some challenges to the PV installer. Some options the installer considered was waiting until after dark, or using a tarp to block illumination to the modules. With the DC disconnect opened, the installer measured about 2 amps of current still within some portions of the array. This was likely the result of multiple ground faults. In the end, the installer chose to use electrical voltage rated rubber gloves and an insulated wire cutter to begin cutting wires to the modules on the roof. The rubber gloves were needed because blind reaching under a damaged module was often needed to get access to these wires, and it was not immediately known if the wires were damaged and bare conductor was present. Also, it was possible that frames of modules and/or sections of the aluminum mounting rail could be energized as the grounding system became compromised during the fire. The installer also used a hand-held voltmeter to periodically check voltages on exposed conductive parts. As each module was disassembled from the rail, and cut free from the string, it was handed down to a person at ground level for safe storage.

An analysis of the modules on the ground showed that modules C1, C2, D1, D2, and E1 had been completely destroyed by the fire. Module E2 had a damaged bus and was producing about half rated voltage and current. The remaining modules were fully functional. Figure 181 and Figure 182 illustrate the extent of damage to the array and a voltage produced by the damaged modules.

Figure 181 Installer identifies hazardous voltage

Figure 182 Assessing Damaged Modules

Figure 183 provides a view of energized bare conductors and broken, melted metal frames.

Figure 183 Bare energized conductors contacting broken rails and metal frames

Figure 184 through and Figure 186 illustrate the technique used during the disassembly of the array after the experiment.

Figure 184 Looking under module for dangers

Figure 185 cutting leads

Figure 186 Work continues closer to damaged modules

Figure 187 and Figure 188 provide view of the damage to the roof surface and back of a PV module.

Figure 187 Roof after modules removed

Figure 188 Module E2, partial damage

13.4.4. Roof Fire 2 Started Under Modules (B2)

For this second experiment with starting a fire under the modules, the bunker with modules on an aluminum rail mounting system was again reconstructed similar to the previous test with modules. This involved a test array consisting of 20 modules, with two parallel strings of 10 modules wired in series.

The fire load consisted placing 25 pounds of pine straw completely under modules E1, E2, F1, and, F2, and half under modules D1 and D2.

This second experiment with a roof fire was conducted on April 21, 2011. The weather conditions at the time of the test were mostly sunny, and the solar irradiance was approximately 925 W/m^2 incident to the roof. The initial power conditions being produced by the PV array at the beginning of the test were 3600 watts, 367 volts DC, and 225 volts ac. The pine straw was ignited between modules E2 and F2. The following observations were made as the fire test progressed:

After 2 minutes flames were observed coming from between modules in columns D and E, and module E2 was already beginning to sag. After 2 minutes and 20 seconds, the inverter turned off, and the array voltage dropped from about 370 volts to 180 volts. After 7 minutes there was considerable open flames coming from the pine straw and heavy gusts of wind out of the north (array was facing east). The center of the array was collapsing around columns D, E and F. After 12 minutes there was still some open flaming being observed at the top of the array, but most of the pine straw had burned off and producing mostly smoke. Making visual observations from the inside of the bunker, after 24 minutes there was charring noticed on the inside of the roof, and after 32 minutes there was some smoke seen. At 48 minutes, a flame was first seen on the inside of the roof, and after 60 minutes, embers from the OSB roof deck were seen falling from inside the roof. The open flame on the inside of the roof at this point was about 2 feet in length. After 1 hour and 20 minutes, the test was stopped and water was applied. The array voltage was still 140 volts at the end of the test.

The modules were removed from the roof using the same precautions as done previous with the first test. An analysis of the modules showed that modules C1, D1, E1, F1, G1, D2, E2, F2, and G2 had been completely destroyed by the fire. The remaining modules were fully functional. It was noted that functional module B1 also had bare conductor exposed.

Figure 189 and Figure 190 illustrate the fire extension of the debris during the experiment.

Figure 189 Ignited pine straw under modules

Figure 190 Smoke after pine straw burns

Figure 191 illustrates the damage to the array prior to breaching into the attic.

Figure 191 Broken glass and debris

Figure 192 and Figure 193 provides a view of the underside of the wood deck prior to breaching into the attic.

Figure 192 Smoke developing on inside of roof

Figure 193 Charring on inside of roof

Figure 194 and Figure 1967 illustrate the breaching and ignition of the underside of the roof deck**.**

Figure 194 Flaming of underside of roof deck

Figure 195 Close up of flaming

Figure 196 and Figure 197 provides a view of the extent of damage to the array from the experiment.

Figure 196 Destroyed modules on roof

Figure 197 Bare Conductors in Debris on Roof

14. Summary of Findings

As a result of the significant increased use of PV systems on residential and commercial structures, firefighters and fire safety officials have raised concerns about the potential risks when PV systems may be part of the fire hazard or impact fire department operations. The electrical and fire hazards associated with PV systems under normal operating conditions have been known for some time, and the voluntary certification of these products and enforcement of installation codes minimize potential electrical and fire hazards. Fortunately, the limited number of fire events that have occurred and have not resulted in fire fighter fatalities. However, a limited body of knowledge and insufficient data exists for the fire service community to fully understand the risks to the extent that standard operational procedures have been developed and widely used amongst individual fire departments.

To help address these concerns, UL conducted fire and electrical performance experiments to identify and quantify the electrical shock hazard that may be present to firefighters during the suppression, ventilation, and overhaul activities associated with a fire involving the PV equipment. The data from this research project is intended to develop scientifically based data which can be used as the foundation for firefighter training and techniques for safely and effectively combating fires with PV installations. The following summarizes these research findings.

Before you explore this section, it is very important to understand this information and these considerations as they pertain to the types of PV systems used in these experiments as compared to your department's response area and available resources.

- One important factor to keep in mind is the capabilities and resources available to your particular department. If your department has 3 person staffing on an engine and your mutual aid is 20 minutes away, you should look at these considerations differently than if your department has 6 person staffing and you expect 4 engines and 2 trucks on the scene in 10 minutes.
- There are no two PV fire events that are the same and not every scenario has one answer that is correct every time. Most of the time, it depends on a number of variables.
- Even in these controlled experiments, with the same experimental test rig and fuel load, there were differences in how the fire impacted the PV system. Damage to the PV systems components (modules, wiring, combiner boxes, racking system, inverters, etc.) is event specific. The resultant potential electrical hazard and means to mitigate that hazard will vary. These tactical considerations are not meant to be rules but to be concepts to think about, and if they pertain to you, by all means adapt them to your operations.

1. The electric shock hazard due to application of water is dependent on voltage, water conductivity, distance and spray pattern. A slight adjustment from a solid stream toward a fog pattern (a 10 degree cone angle) reduced measured current below perception level. Salt water should not be used on live electrical equipment. A distance of 20 feet had been determined to reduce potential shock hazard from a 1000 Vdc source to a level below 2 mA considered as safe. It should be noted that pooled water or foam may become energized due to damage in the PV sytem. A summary of the distances and spray patterns which measured safe (< 2 mA) and perception (< 40 mA) currents for various PV system voltages is shown in Appendix A.

2. Outdoor weather exposure rated electrical enclosures are not resistant to water penetration by fire hose streams. A typical enclosure will collect water and present an electrical hazard.

3. Firefighter's gloves and boots afford limited protection against electrical shock provided the insulating surface is intact and dry. They should not be considered equivalent to electrical PPE.

4. Turning off an array is not as simple as opening a disconnect switch. Depending on the individual system, there may be multiple circuits wired together to a common point such as a combiner box. All circuits supplying power to this point must be interrupted to partially de-energize the system. As long as the array is illuminated, parts of the system will remain energized. Unlike a typical electrical or gas utility, on a PV array, there is no single point of disconnect.

5. Tarps offer varying degrees of effectiveness to interrupt the generation of power from a PV array, independent of cost. Heavy, densely woven fabric and dark plastic films reduce the power from PV to near zero. As a general guide, if light can be seen through a tarp, it should not be used. Caution should be exercised during the deployment of tarps on damaged equipment as a wet tarp may become energized and conduct hazardous current if it contacts live equipment. Also, firefighting foam should not be relied upon to block light.

6. When illuminated by artificial light sources such as fire department light trucks or an exposure fire, PV systems are capable of producing electrical power sufficient to cause a lock-on hazard.

7. Severely damaged PV arrays are capable of producing hazardous conditions ranging from perception to electrocution. Damage to the array may result in the creation of new and unexpected circuit paths. These paths may include both array components (module frame, mounting racks, conduits etc.) and building components (metal roofs, flashings and gutters). Care must be exercised during all operations, both interior and exterior. Contacting a local professional PV installation company should be considered to mitigate potential hazards.

8. Damage to modules from tools may result in both electrical and fire hazards. The hazard may occur at the point of damage or at other locations depending on the electrical path. Metal roofs present unique challenges in that the surface is conductive unlike other types such as shingle, ballasted or single ply.

9. Severing of conductors in both metal and plastic conduit results in electrical and fire hazards. Care must be exercised during ventilation and overhaul.

10. Responding personnel must stay away from the roofline in the event of modules or sections of an array sliding off the roof.

11. Fires under an array but above the roof may breach roofing materials and decking allowing fire to propagate into the attic space.

15. Future Research Needs:

This project was the first experimental investigation of the general impact of PV on fire department suppression, ventilation and overhaul operations. Although the team made every effort to be comprehensive, the work is not exhausted as insights obtained from this research indicate a need for additional data, in particular to investigate hazards during overhaul operations.

Following a fire department's ventilation and suppression operations, confirmation that the fire is extinguished (overhaul) is a hands-on effort requiring removal of building components to look for fire extension or hot spots. Potential sources of ignition are required to be rendered safe. Typically, disconnection from the local utility power mitigates potential sources of electrical ignition or hazards. PV systems present a non-typical challenge in that they are capable of producing power after removal of the local utility supply. While multiple power sources is not typical, particularly in residences, the trend toward alternate sources of energy is apparent. The impact on firefighting operations to address multiple power sources has been documented [27] and the procedures to address them currently exist for telecommunications central offices and data centers whose continuous service is attained by onsite generators and batteries in the event of local utility interruption. A recent report by The Fire Protection Research Foundation[28] *Fire Fighter Safety and Emergency Response for Solar Power Systems* provides an excellent summary of current state.

In addition, system components are located in multiple sections of a structure including the roof, attic, interior and exterior walls. Damage to the components may be the result of a fire within the structure and not readily apparent or observed. The system's circuitry may have been compromised from thermal or mechanical forces as a result of the fire. Individual modules, although damaged have been shown to be capable of generating power. The hazards associated with the mitigation and depowering of a fire damaged PV system warrants further work.

As new alternative energy technologies are developed and deployed, consideration must be given to for operational needs of the fire service to minimize personal risk as they perform their duties for their customers' safety, the general public, each of us.

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[27] Illinois Bell Telephone Company, Illinois. Office of the State Fire Marshal, Illinois Commerce Commission, Forensic Technologies International Corporation, Office of the Illinois State Fire Marshal, 1989

[28] Casey Grant, *Fire Fighter Safety and Emergency Response for Solar Power Systems* (The Fire Protection Research Foundation, 2010)

16. Acknowledgements:

Without the financial support of the Department of Homeland Security’s Assistance to Firefighters Grant Program’s Fire Prevention and Safety Grants this research would not be possible. In particular the staff members; Dave Evans, Kathy Patterson, Ellen Sogolow and Maggie Wilson provided encouragement and support.

In addition, wish to acknowledge the many contributions of Paul Courtney, Engineering Technician, UL Corporate Research toward the successful completion of the project.

This research activity was conducted to assist the fire service develop safe operational tactics and with direct fire service participation. This project benefited from the guidance and input of the following Fire Departments and training organizations:

SAN JOSE FIRE

KERN COUNTY FIRE DEPT.

CALIFORNIA DEPARTMENT OF FORESTRY & FIRE PROTECTION CAL FIRE SINCE 1885

DELAWARE COUNTY EMERGENCY SERVICE TRAINING CENTER

FIRE CHICAGO DEPT.

NORTHBROOK FIRE DEPT.

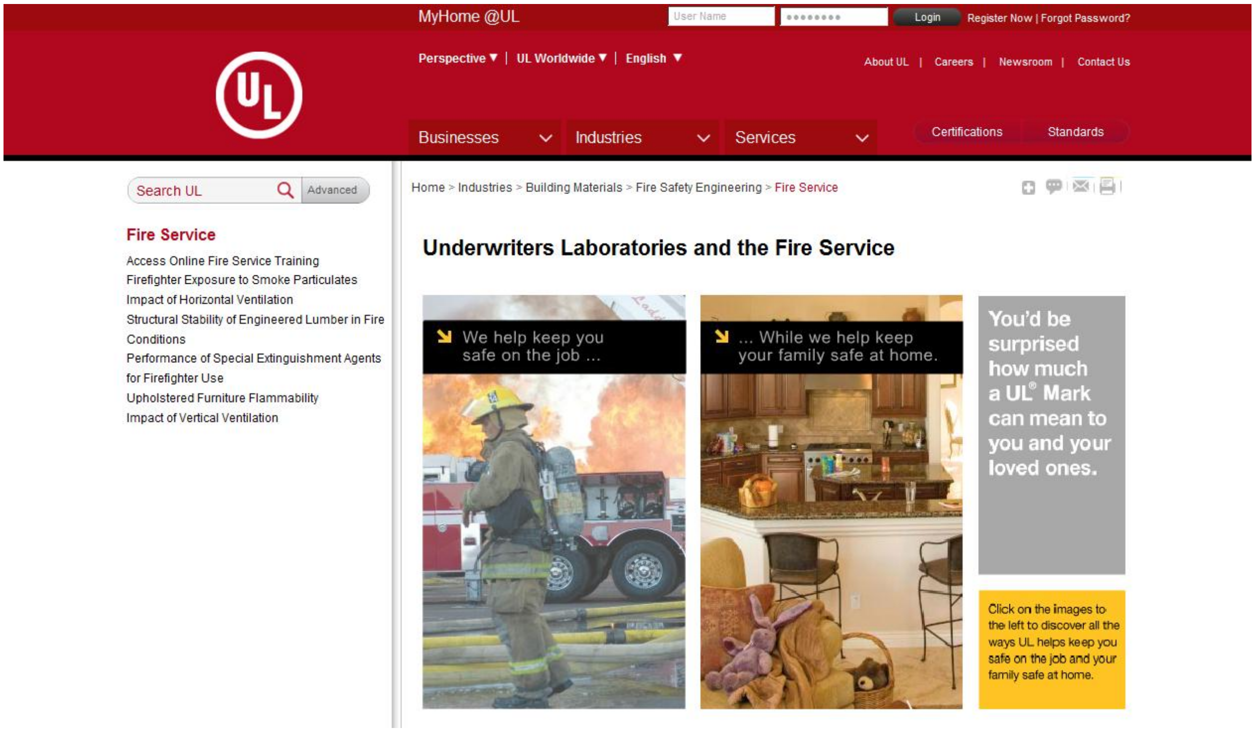
COUNTRYSIDE FIRE DIST.

17. Dissemination

As this project was the result of an Assistance to Firefighters grant, an objective of the project was to make the information readily available to the fire service. To accomplish this, both this formal report and a web based interactive outreach is available to the fire service at the following website:

www.ul.com/fireservice

In addition to this project, information is available on other research projects including lightweight wood construction, smoke exposure, vertical ventilation and upholstered furniture flammability.



Underwriters Laboratories and the Fire Service

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APPENDIX A

Summary of distance, current and voltage hazards measured during the experiments.

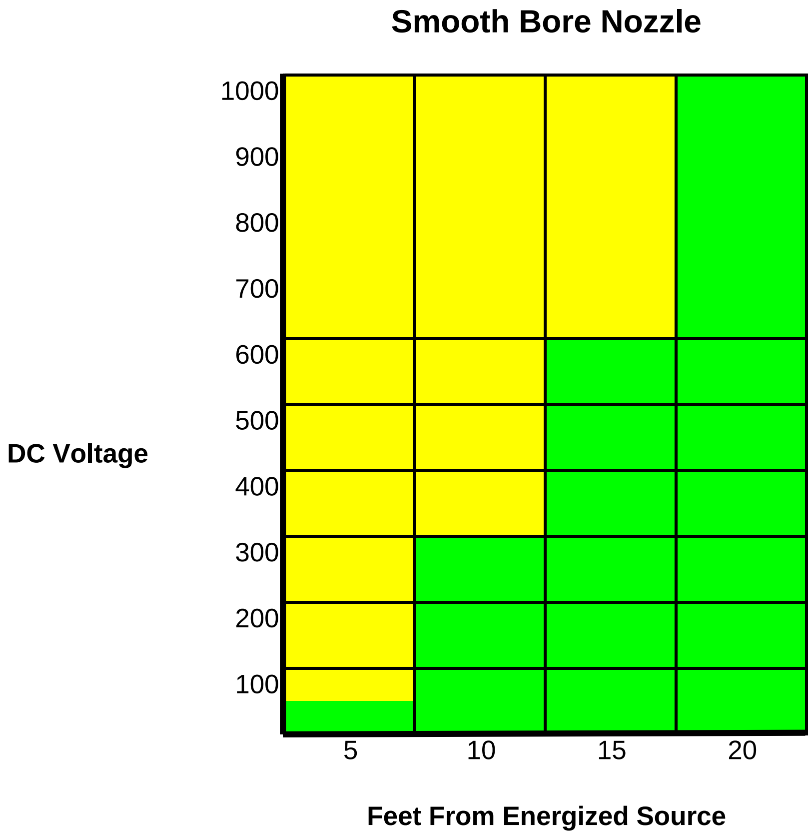


Figure 198 Smooth Bore Nozzle Shock Hazard Levels

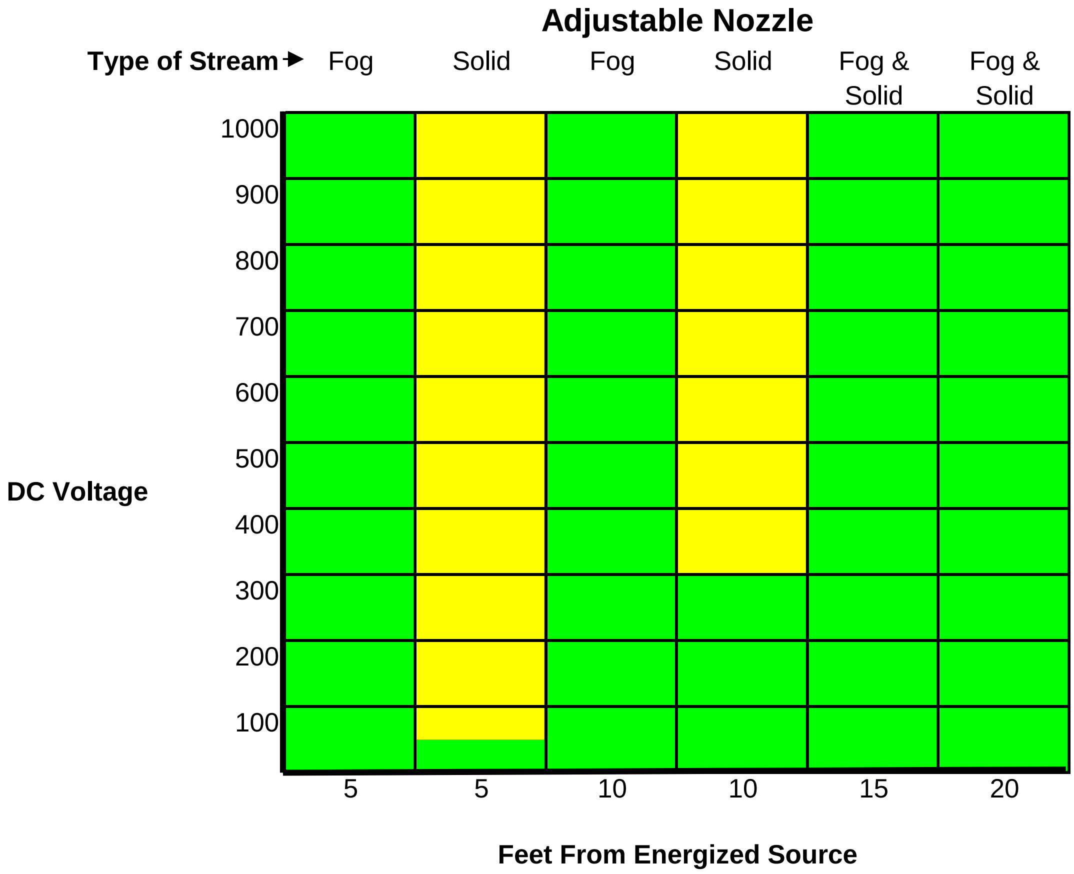
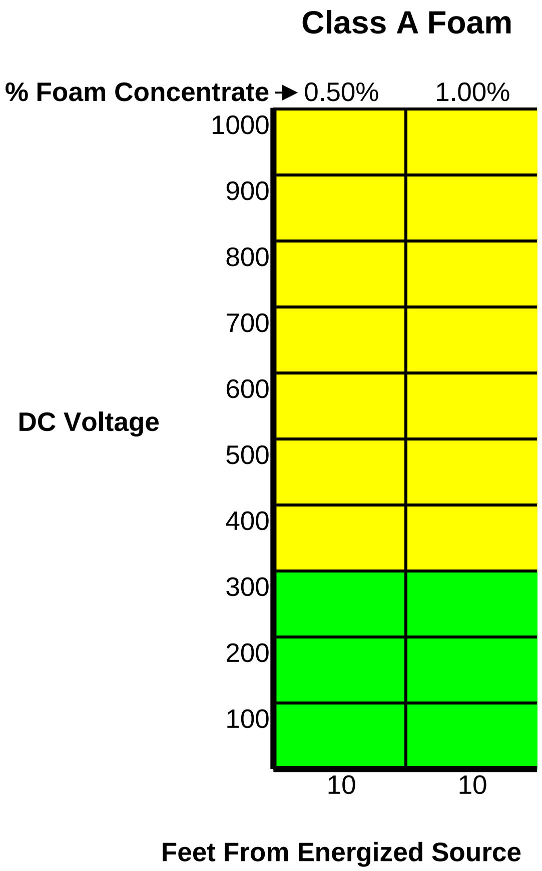


Figure 199 Adjustable Nozzle Shock Hazard Levels



% Foam Concentrate →	0.50%	1.00%
1000	🟨	🟨
900	🟨	🟨
800	🟨	🟨
700	🟨	🟨
600	🟨	🟨
500	🟨	🟨
400	🟨	🟨
300	🟩	🟩
200	🟩	🟩
100	🟩	🟩
	10	10

Figure 200 Class A Foam Shock Hazard Levels