STUDY OF PARTIAL DISCHARGE EFFECTS OF PV BACKSHEET COMPONENT FILMS. STRUCTURE PROPERTY RELATIONSHIPS, AND MEASUREMENT CONSISTENCY

Nancy H. Phillips[1], , Brad Givot[1], Bill O'Brien[1,] L. Charles Hardy[1]
Jaylon Loyd[2], Wolfgang Schoeppel[3], Carsten Jaeger[3]
Christof Humpert[4], Ralph Schumacher[4] Christian Knoll[4],
[1]3M Company, St. Paul, Minnesota, USA
[2]3M Company, Austin, Texas, USA
[3]3M Company, Neuss, Germany
[4]Institute for Electrical Engineering, University of Cologne, Cologne, Germany

ABSTRACT

Partial Discharge is one of a number of tests defined in IEC61730-2, which specifies properties of photovoltaic modules and components for safe electrical and mechanical operation during their expected lifetime. The test is of practical importance in the development and manufacturing of backsheet barrier films because of the limitations it places on film thickness. The objective of this study was to understand the relationship of this test to film properties. Although simple to describe, in practice, the test is difficult to perform with consistency. We have found that this test performed in air usually provides consistent relative behavior, but that absolute values can vary on different days, or in different laboratories. We have tested several materials with varied thickness, and found a linear relationship between Ve and square root of film thickness when measured in air, in line with a surface discharge phenomenon. This paper will describe efforts to define and understand sources of variability in both inter and intra laboratory measurements, and on the measurements of some typical component materials of PV backsheets.

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BACKGROUND

IEC 61730 describes the testing requirements for photovoltaic (PV) modules in order to provide safe electrical and mechanical operation during their expected lifetime. Specific topics are provided to assess the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stresses. Most of the tests are carried out on a module, and the backsheet construction can impact module performance on these tests. Partial discharge is the only component level test required for a backsheet. For many backsheet constructions, this measurement will discriminate between potential materials or limit the thickness of the materials selected.

The partial discharge test has a long history of use in measurement of materials exposed to high voltage during use,[2] and is included in a number of IEC specifications: IEC 61730 is the parent PV safety standard which calls for PD component test; IEC60664 addresses insulation coordination for equipment within low voltage systems, and describes high voltage dielectric tests with DC and AC and combinations. IEC60270 "High Voltage Test Techniques" deals with basic setup, coupling devices, wideband, narrowband, calibration, calibrators, uncertainty, guidance on test procedures, and discrimination of partial discharges from external interference.

With IEC61730 in the process of revision, many aspects of testing of PV materials and modules are under discussion. The area of partial discharge has seen significant debate in the past year. Within that broader area, we (the authors) have been party to personal and IEC level discussions in the following areas:

- The purpose of the test
- Inter- and intra- lab data consistency
- Test environment (air v. oil)
- Ease of testing
- Relationship of materials structure to V_e
- Applicability of an AC test to a DC system

In a broader context, there is a very apparent lack of unity among stakeholders as to understanding the relevance of the test, specifically:

- What field failure mode is the test intended to replicate?
- Is this test, as performed, relevant to PV safety?
- Is there a better test, or test method?

We have given consideration to each of these areas, but our efforts have endeavored to focus on three areas: noise mitigation, data consistency, and structure/property understanding.

RESULTS AND DISCUSSION

3M has partial discharge equipment at three internal research and development laboratories. Our primary site is at 3M's global headquarters in Saint Paul, MN, USA, where we have utilized NVLAP certified and FCC approved shielded enclosures. Additionally, we have utilized 3M's High Voltage Development Laboratory in Austin, Texas, and at 3M's European research center in Neuss Germany. We have also contracted with the Institute for Electrical Engineering, University of Cologne, Cologne, Germany, and have strongly benefited from their established knowledge in this area.

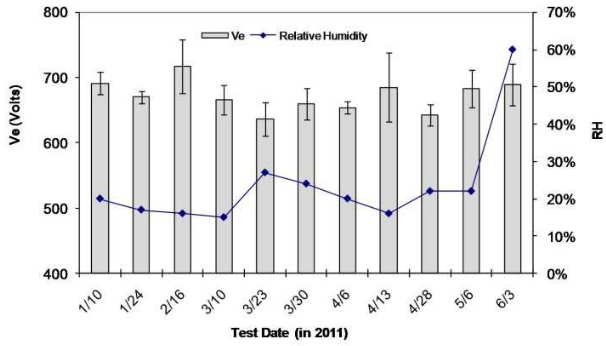
The test is simple to describe, and at first glance seems analogous to a test of breakdown strength. In both, a material is placed between two electrodes, and the voltage raised until current or charge is observed. For the breakdown strength measurement, with typical voltages measured in kVs and the current in amps, the test is completed when a hole is burned through the sample. In the partial discharge test, voltages are an order of magnitude lower, and the charge is measured in pico (10^{-12}) coulombs per 60 hz cycle. After the discharge has been initiated (V_i), the voltage is held at a $V_{\mathbf{max}}$ (=V_i +10%) for 60 seconds, and then lowered until the charge level falls below the noise threshold, defined as the extinction voltage $V_{\mathbf{e}}$. This test is seemingly non-destructive, in that samples have been tested numerous times without showing any effect due to voltage exposure.

Noise mitigation. This test is deceptively simple to perform; and difficult to put into practice. One gains an appreciation for stray electrical signals when looking a charge levels of *femto* (10^{-15}) coulombs. The efforts taken to reduce noise to the required levels are described in a companion presentation at this conference[3]. With the noise mitigation techniques described there, we are now able to routinely run the test under the required noise minimum of 1 picocoulomb.

Data consistency. We were interested in correlating data obtained at 3M's internal facilities with data obtained at certified testing facilities, as there are no generally accepted reference materials, or calibration standards. A prerequisite was to demonstrate internal data consistency. Figure 1 shows the $V_{\mathbf{e}}$ data obtained with the same set of samples (3M 990 Series PET, 112 micron thickness) on multiple days. These results show relatively consistent results, and are representative for other materials.

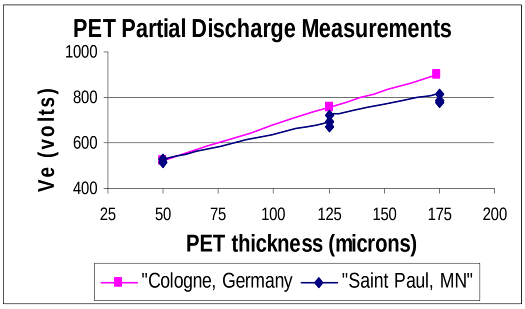
Our testing is not carried out in a CTH room, which adds a source of variability; a side benefit is our ability to see the impact of the high humidity variations that come with the high seasonal variances of Saint Paul, Minnesota, on $V_{\mathbf{e}}$ measurements (Figure 1). Neither the large inconsistencies nor the typical variability are directly accounted for by humidity considerations.

Figure 1. Partial Discharge of PET, multiple days



Inter-lab comparisons were made on several thicknesses of 3M 990 PET as shown in Figure 2. The results match well for thinner materials, but discrepancies increase with thickness. Some sources of variance under consideration are fixture design (parallelism of the plates, electrode radius of curvature), atmospheric pressure, and humidity.

Figure 2. Extinction Voltage of PET films, varying thickness, at 3M-St. Paul and University of Cologne.

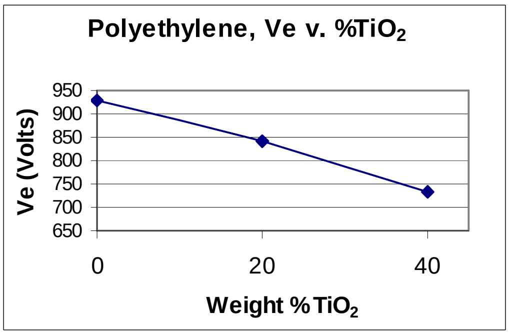


Structure / Property Correlation

Partial discharge is well understood as a mechanism for electrical degradation of polymers.[4] Signals have been segmented into four classification categories[5]. corona (local environment), surface discharge, internal discharge, and noise. Internal discharges are of particular interest for PV module safety, described in IEC 60664: "partial discharges can occur in these gaps or voids at voltages far below the level of puncture (breakdown strength) and this may influence decisively the service life of the solid insulation".

We performed the partial discharge test on a number of polymeric films, with variations in the bulk, internal defects or inclusions, and surface defects. The results were surprising in their similarity, with thickness as the primary factor. The range of samples compared includes: a thick monolayer film versus same thickness stacks composed of multiple thin layers (contains air inclusions); PET, before and after 80 days of 85/85 (morphological and molecular weight changes), PET, before and after a 140 micron hole puncture. No statistically significant difference was seen between the listed comparators. Results were mixed when comparing films with and without TiO_2. At a “defect level” of TiO_2 (up to 5%), no differences were seen with pigmented versus non-pigmented films of EVA, PET, and THV. As shown in Figure 3, differences were finally seen with higher levels of TiO_2 in polyethylene at higher levels. At these high levels, TiO_2 is effectively part of the bulk.

Figure 3. Partial Discharge of Polyethylene with TiO_2



Murakami and Mizukami[6] have made a thorough study of partial discharge of polymer films in air and oil, and demonstrated that properties in air are strongly related to surface phenomena. He references an empirical model for partial discharge in air[7]:

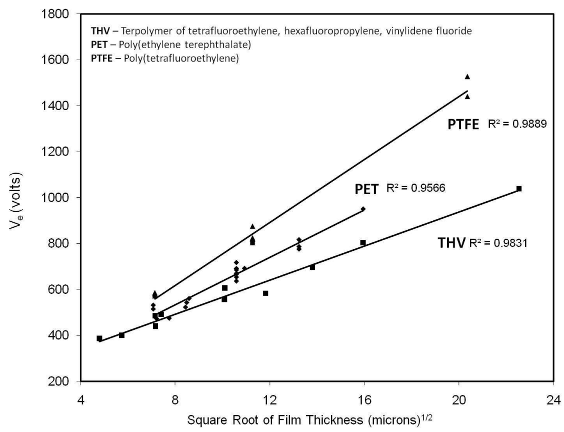
$$V = c\sqrt{\frac{t}{\varepsilon}\cdot\frac{293}{T(°K)}}$$

t = Insulation thickness (mm)
ε= Dielectric constant.

In our laboratories, the partial discharge of a number of materials with different film thicknesses were measured. Figure 4 shows a plot of several of these data sets, with an excellent linear fit for V_e versus $t^{1/2}$. The slopes of these lines have the same rank order as the inverse of the dielectric constant of the corresponding material.

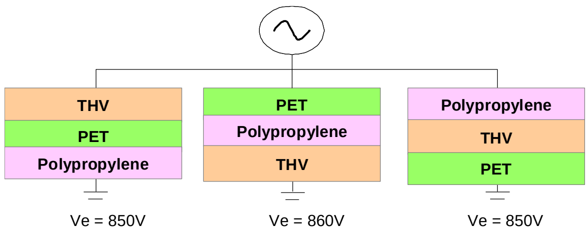
Figure 4. Dependence of Ve on Polymer Thickness

Murakami demonstrated that the electrical activities are occurring at the annulus of the electrode, in the air gap at the curved edge. The results are explained by a model with the air and the film sample acting as capacitors in series. The higher dielectric material pushes the electric field into the lower dielectric field; thus the air will break down at a lower applied voltage for a high dielectric material compared to a lower one.



Multilayer Samples. Three sets of trilayer stacks were prepared, each comprised of ~50 micron film of Film samples of THV, PET, and polypropylene, but with a different polymer at the top of one stack, facing the working electrode (Figure 5). Extending the working model to four capacitors in series, the order of the films should make no difference to the electric field in the air gap at the discharge voltage, and the air breakdown should occur at the same $V_{applied}$ for each set. As predicted by that model, the extinction voltages for the three sets were the same.

Figure 5. Partial Discharge of multilayer stacks, different surface materials.



Surface effects. Out of the four categories of partial discharge listed earlier, both surface and internal discharges are of concern with regards to potential for erosion of insulating material, and subsequent deterioration of its insulating properties.[8] It is well known that an air corona can impact the surface of a polymer[9,10,11,] as a result of secondary reactions following the ionization of air:

1. *Breakdown of Air:*

   $\text{Air} + e^- \longrightarrow O\bullet, O_3, NO_3\bullet.$

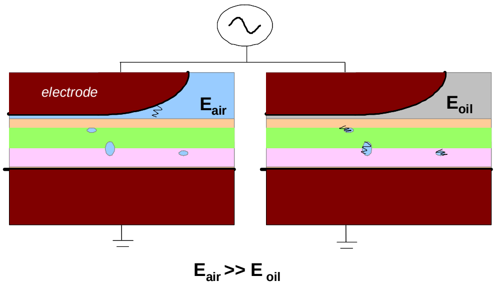
2. *Polymer degradation:*

   $O\bullet, O_3, NO_x\bullet, + R_3C\text{-}CR_3 \longrightarrow \text{Chain scission}$

While the materials next to the working electrode *may* erode when adjacent to an air corona, significant differences in the rate of degradation of different polymeric materials are expected, related to their chemistry. Polypropylene, for example, is much more susceptible to degradation than PET or THV, and in the stacks described above, would be expected to have greater decomposition than the others. This test suggests an inverse relationship between susceptibility to degradation and dielectric constant; this is inappropriate, as the same factors that give some materials a high dielectric constant, also cause enhanced stability (e.g. fluoropolymers). Quantification of the relative degradation levels is currently under investigation, as well as the difference expected from AC versus DC corona exposure (partial discharge is an AC test.)

Behavior in oil. Many dielectric properties measurements are conducted in oil for the purpose of excluding air breakdown from the measurement. The difference between measuring partial discharge extinction values in air and oil was well demonstrated for PET by Murakami, who found a >5x increase for PET measured in air versus oil (results in oil were inconsistent, likely due to limitations of the equipment at the higher voltages needed to see partial discharge in oil).

Figure 6. Effect of oil on the location of discharge.



The ability to detect enclosed air in an oil environment was demonstrated using a microstructured film laminated to a pressure sensitive adhesive, with increasing amounts of pressure (Figure 7). This had the effect of creating air bubbles of different sizes, which were measured microscopically.

Figure 7. Schematic of films with enclosed air.

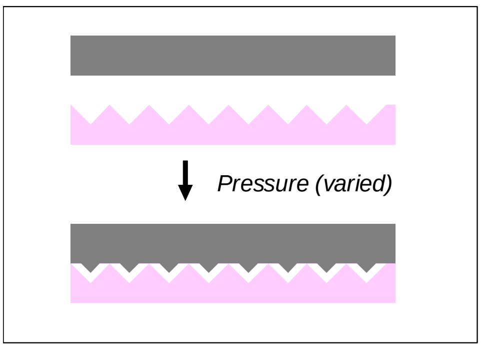


Figure 8 shows a typical micrograph, with the shape of the air bubble defined by the microstructure, and the size of the bubble defined by the applied pressure.

Figure 8. Micrograph showing 114 micron entrapped airair bubbles in a multilayer, microstructured film.

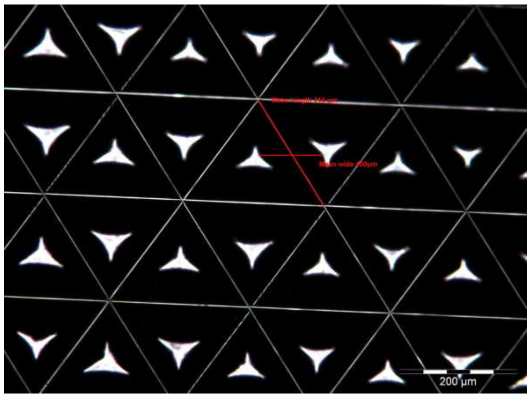
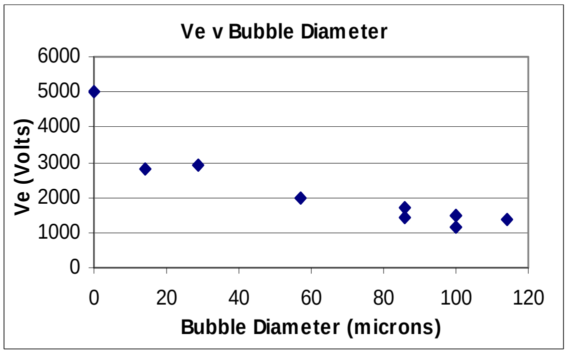


Figure 9 shows the measured extinction voltages for these samples with air bubble widths ranging from 0 to 114 microns. Whereas samples measured in air had little or no sensitivity to air inclusions (recall the sample with pin hole, and the stacked layers of film), these samples shows a large sensitivity to the presence of air. With no entrapped air, the extinction voltage is >5 kV, too high to measure. With the smallest bubble size, Ve quickly drops below 3 kV, and then continues to decrease to ~1.5 kV, a typical level for ~400 micron films – measured in air. This voltage level is maintained for larger bubble sizes. The minimum voltage level presumably arrives when the air gap has reached the Paschen's law minimum.

Figure 9. Partial Discharge (in oil) of laminates with entrapped air.



CONCLUSIONS

We've seen a significant evolution of our hypothesized model of partial discharge in air throughout the course of this work. Initially, we assumed that the test was interrogating defects within the sample. However, our work has shown that when carried out in air, the measurement reflects the Paschen's law breakdown of the air between the curved perimeter of the electrode and the sample.

It appears that partial discharge behavior in air is only related to a material's structure in so far as the material's dielectric properties impact the partitioning of the electric field, and thus the voltage to which the air is exposed. A high dielectric material will act to "push" the electric field toward the air gap, resulting in a higher electric field for the air gap, and thus a lower observed V_e.

We have not observed any evidence to suggest the test is identifying any defects which could lead to degradation after long term exposure to typical voltages seen in actual field applications.

As for surface degradation due to corona, because the same extinction voltages can be attained when materials of very different reactivity are exposed to the working electrode, this test is unlikely to correlate to susceptibility of an insulating material to electrical degradation.

As this test continues in IEC 61730-2, significant consistency, and inter and intra-lab correlation issues should be addressed. Of higher importance at this stage, is for stakeholders to build consensus on field failure modes, relevance to PV safety, and PV cost, and work to define a test that demonstrably addresses field safety, product cost, and ease of testing issues.

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