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Pulsed Electroacoustic Analysis Capabilities at NASA Glenn Research Center

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Pulsed Electroacoustic Analysis Capabilities at NASA Glenn Research Center

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Summary

The High Voltage Testing Laboratory at the NASA Glenn Research Center is equipped with a pulsed electroacoustic (PEA) analyzer to study space charge phenomena in dielectric materials. Dielectric materials such as those used in high-voltage insulation systems are of great interest due to their crucial role in withstanding high voltages and avoiding electrical breakdown in electrified aircraft power systems. Current research is underway for the development of novel lightweight electrical insulation, and the thorough evaluation of these materials is required. The PEA instrumentation at NASA Glenn is a nondestructive method to evaluate the space charge phenomena, which can give a unique insight on the feasibility and lifetime of material systems. The instrumentation capability and initial results are reported here.

Nomenclature

EAP	electric aircraft propulsion
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
PD	partial discharge
PEA	pulsed electroacoustic
PEEK	polyether ether ketone
PEI	polyetherimide
SOA	state-of-the-art

Introduction

NASA will require electric-based power systems to make air travel more efficient, safer, and quieter and also allow space missions to expand research on the Moon. The aeronautics and space environments exhibit extreme temperatures, pressures, and radiation exposures, creating difficult conditions for standard power system operation. Unique and specialty designed systems that can survive those conditions are of great interest and need. Specifically in aeronautics, future electric aircraft propulsion (EAP) systems will require increased efficiencies that can be met through integration of electric power on the megawatt scale (Ref. 1). It is critical for power system solutions to be high power and low mass. High-voltage systems can meet the power requirements for electric aircraft propulsion. The integration of higher voltages allows for conductor diameters to be reduced, thus reducing the overall mass of the conductor. A large weight component on power systems are the miles of wiring and power distribution cables (Ref. 2). Decreasing the weight of cables could improve the overall fuel efficiency of the aircraft, and when applied to spacecraft applications, this fuel efficiency may show an even greater effect (Ref. 3).

Novel power distribution cable design can significantly improve the efficiency, operation lifetime, and safety of the power system. Electrical components exposed to extreme environments (Ref. 4) are at risk of charge accumulation which may cause failure or breakdown of insulative materials (Ref. 5). Extreme environments such as high-altitude conditions experienced by aircraft can create charge accumulation as described by Paschen's Law as referenced in NASA Handbook-4007 (Ref. 6). The Paschen curve illustrates the dependency of the breakdown voltage of a dielectric material on conducting surfaces and altitude. If the spacing of the conductor remains constant, the breakdown voltage of the dielectric material decreases as altitude increases. To prevent breakdown with current state-of-the-art (SOA) materials, the distance between conductors (i.e., the thickness of insulation used in the system) must be substantially increased. This condition shows the increased chance for breakdown of crucial insulation materials to occur in aircraft. It also illustrates the need for high performance and low mass dielectric materials.

To prevent failure modes from occurring and damaging electrical systems, dielectric materials need to be evaluated through each failure mode type: thermal, mechanical, electrical, and chemical. Numerous studies of thermal aging, mechanical damage testing, and chemical compatibility have become standard evaluation techniques and have been conducted on both SOA materials and novel research materials (Refs. 7 to 9). More focus on understanding electrical failure modes is needed to fully understand the performance of dielectric insulation

*Currently retired.

materials for high-voltage (≥300-V) operation in extreme aerospace environments.

Electrical failure modes of dielectric materials include internal partial discharge (PD) in the form of electrical treeing, external partial discharge through surface electrostatic discharge or corona, and internal space charge accumulation. Space charge phenomena occurs when electricity is applied to a dielectric material. Surface charges can be injected into a dielectric material in the presence of an electric field. Additionally, bound charges inside a dielectric can be mobilized from an external electric field. This charge accumulation creates regions of high charge densities often as voids, that can affect the electrical properties of the dielectric. Over time, the space charge accumulation can lead to dielectric breakdown. Understanding whether materials accumulate charge and determining these locations is critical because when these embedded charges are trapped, the potential corona or discharge events can cause catastrophic failure to the whole power system.

Pulsed electroacoustic (PEA) analysis is a nondestructive method for evaluating dielectric materials under electric stress (Refs. 10 and 11). The pulsed electroacoustic method works by applying a high voltage to a dielectric film sample that is placed between two electrodes. The electric field that travels through the sample creates vibrations that are then converted to an electrical signal. This signal is presented as a waveform that can be analyzed to show the amount of space charge accumulated as well as the depth of trapped charges in a material (Refs. 12 and 13).

The PEA analyzer as seen in Figure 1(a) was purchased from Box Elder Innovations, LLC, and was custom built for the unique research needs of Glenn and is located in the High Voltage Testing Laboratory. This instrument comes equipped with a high-voltage pulse generator, a high-voltage AC (HVAC) power supply, a high-voltage DC (HVDC) power supply, a test fixture heater, and two interchangeable sensors for materials with varying thicknesses. The HVAC power supply operates from 0 to ±10 kV (0 to 20 kV peak to peak) AC power. The HVDC power supply operates from 0 to 20 kV DC power. The test fixture heater allows for controlled testing from ambient temperature up to 60 °C. The PEA test fixture as seen in Figure 1(b) is composed of a top high-voltage input electrode and a bottom electrode equipped with a sensor module. The bottom electrode is designed so that it can be easily changed out to match the testing material. A 9-µm sensor is used for higher frequency and thinner samples, and a 28-µm sensor is used for lower frequency and thicker samples.

Figure 1.—Pulsed electroacoustic analysis. (a) PEA analyzer. (b) PEA test fixture.

The High Voltage Testing Laboratory at NASA Glenn Research Center is also equipped with multiple materials characterization equipment. The EATON HiPot tester measures dielectric breakdown and withstands voltages up to 60 kV_{AC} (60 Hz) and 84 kV_{DC} with various parallel-plate electrode geometries in both air and oil. The high-voltage dielectric spectroscopy system with multiple parallel-plate electrodes for various sample configurations can be used with a furnace that operates from 25 to 1,000 °C. The high-voltage chamber analyzes materials at reduced pressures to simulate high altitude conditions. This chamber is equipped with partial discharge sensors for testing material performance as a function of environmental conditions and applied voltage. Together, these systems enable NASA Glenn researchers to have the ability to characterize materials and their suitability for various high-power applications that require operating voltages that are equal to or exceed 300 V.

Pulsed Electroacoustic Methods

Prior to PEA data acquisition, the density, thickness, dielectric breakdown strength, and sound speed of each sample needs to be determined. Knowledge of the dielectric breakdown strength is critical to ensure the voltage applied during data acquisition is kept below the breakdown threshold of the material. The dielectric breakdown strengths for each evaluated material are listed in Table I. The maximum applied voltage is determined by multiplying the dielectric breakdown by the thickness of the sample. For example, the maximum applied voltage for the polyether ether ketone (PEEK) 100-µm film is 16 kV/mm * 0.1 mm = 1.6 kV. The dielectric film samples were cut into 2-in. circles, and the thicknesses were measured via a Mitutoyo Absolute digital indicator. Dielectric breakdown strength was either measured via a custom-built Eaton HiPot tester or obtained from the commercial vendor's material data sheets. The speed of sound through the materials were obtained from literature values and verified with the PEA equipment.

The goal of each PEA timed test is to observe the injection of charge into a dielectric sample and to characterize how charge accumulates over time for various dielectric films. Each sample was manually analyzed by the PEA instrumentation to determine suitable pulse generator and scope settings. Once the desired instrument settings were determined, a timed test for each sample was conducted. The parameters of each timed test varied. Table I indicates the settings for each sample tested (i.e., Kapton®, polyetherimide (PEI), and PEEK), including the applied test voltages, which vary depending on material's dielectric breakdown strength.

Kapton® films as seen in Figure 2 were tested as single- and double-layer samples. The single-layer Kapton® samples were tested at 9 kV constant applied voltage as well as a varied-voltage test of 3, 6, and 9 kV as listed in Table I.

PEI films of 127, 250, and 508 µm (Fig. 3) were tested at a constant voltage of 9 kV for 30 min and then 0 kV for 10 min as listed in Table I.

TABLE I.—EXPERIMENTAL SETTINGS FOR DIELECTRIC SAMPLES

Sample		Thickness, µm	Timed test conditions (HVDC)	
			Voltage, kV_{DC}	Time, min
Kapton®	One layer	125	9	30
			0	10
		125	3	10
			6	10
			9	10
			0	10
	Two layer	250	3	10
			6	10
			9	10
			0	10
PEI		127	9	30
			0	10
		250	9	30
			0	10
		508	9	30
			0	10
PEEK		100	0.25	10
			0.5	10
			0.75	10
			1	10
			0	10
		250	1	10
			2	10
			3	10
			0	10

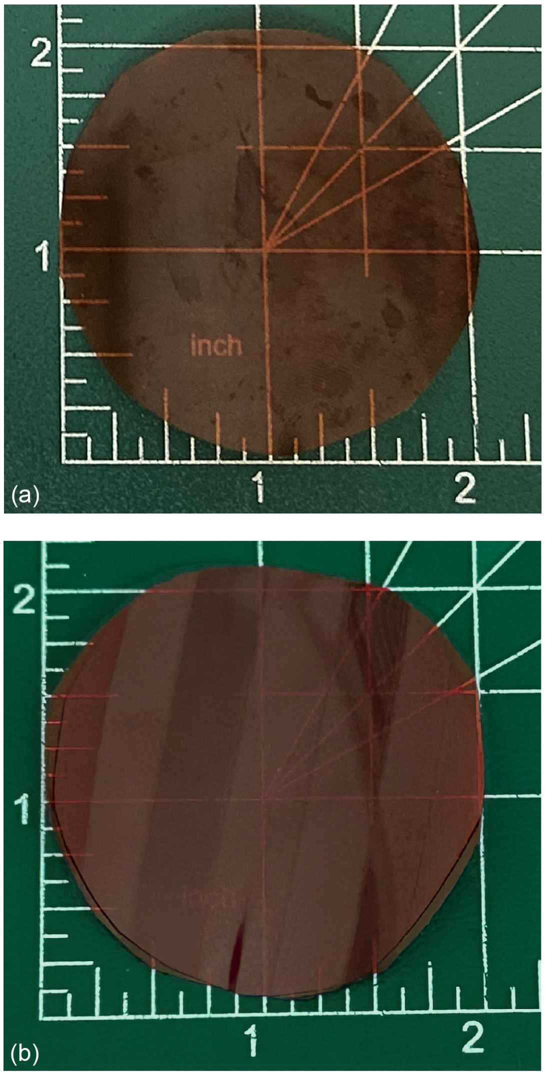


Figure 2.—Kapton® film samples. Diameter dimensions in inches. (a) One-layer 125-μm film. (b) Two-layer 125-μm film.

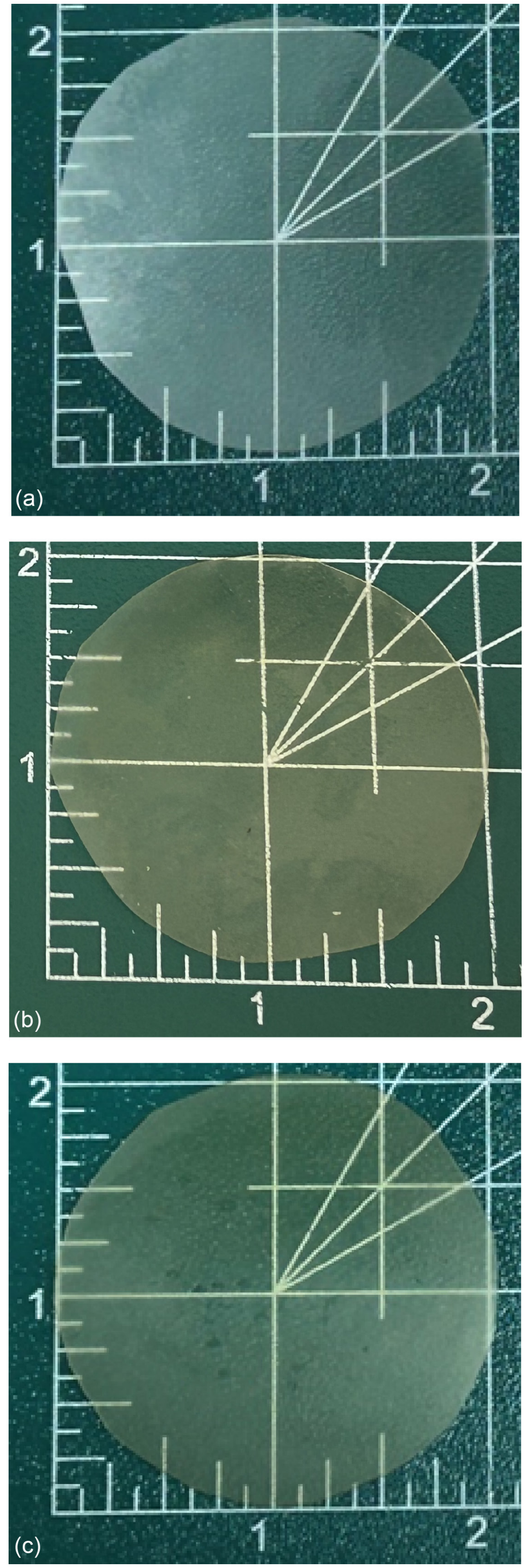
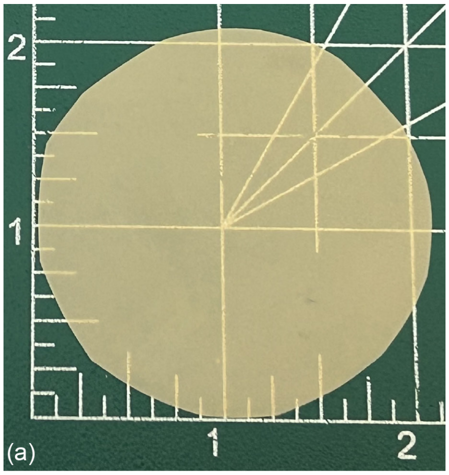


Figure 3.—PEI films. Diameter dimensions in inches. (a) 127-μm film. (b) 250-μm film. (c) 500-μm film.



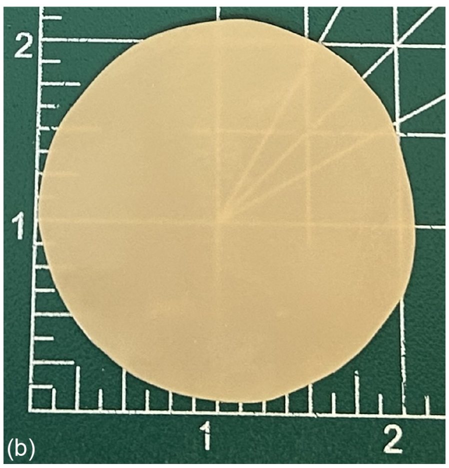


Figure 4.—PEEK films. Diameter dimensions in inches. (a) 100-μm film. (b) 250-μm film.

PEEK films of 100 μm (Fig. 4) were tested at varied voltages of 0.25, 0.5, 0.75, 1, and 0 kV for 10 min each, and the 250-μm films were tested at 1, 2, 3, and 0 kV for 10 min each, as listed in Table I.

In addition to collecting pulsed electroacoustic data for each sample, the PEA instrumentation has the capability of modeling multilayer materials via a ray trace model. This modeling capability can be used for composites with up to seven layers of materials. A ray trace model can be simulated for each sample by importing the identity, thickness, speed of sound, and density of the material. This data can then be used to simulate a model of the waveform structure.

Results and Discussion

The Kapton® films were examined under three distinct testing methods. The purpose of the first test was to evaluate Kapton®, a known aerospace material, under common PEA conditions. This test applied 9 kV for 30 min to evaluate the effect of charge migration and then 0 kV for 10 min to evaluate the charge accumulation. Figure 5 depicts waveforms at intervals of 6 min from this test. The negative peak between 1.025×10^{-6} and 1.05×10^{-6} s was measured to be 50.1 μm and is suspected to indicate the charge accumulation within the Kapton® film. Figure 6 illustrates this test through a two-dimensional intensity map of the waveforms collected over the 40-min experiment. As the voltage is removed, the waveform flattens out, indicating the Kapton® material quickly relaxes when the electric field is removed. Figure 7 summarizes this test through a three-dimensional intensity plot depicting the waveforms in terms of time, position, and amplitude.

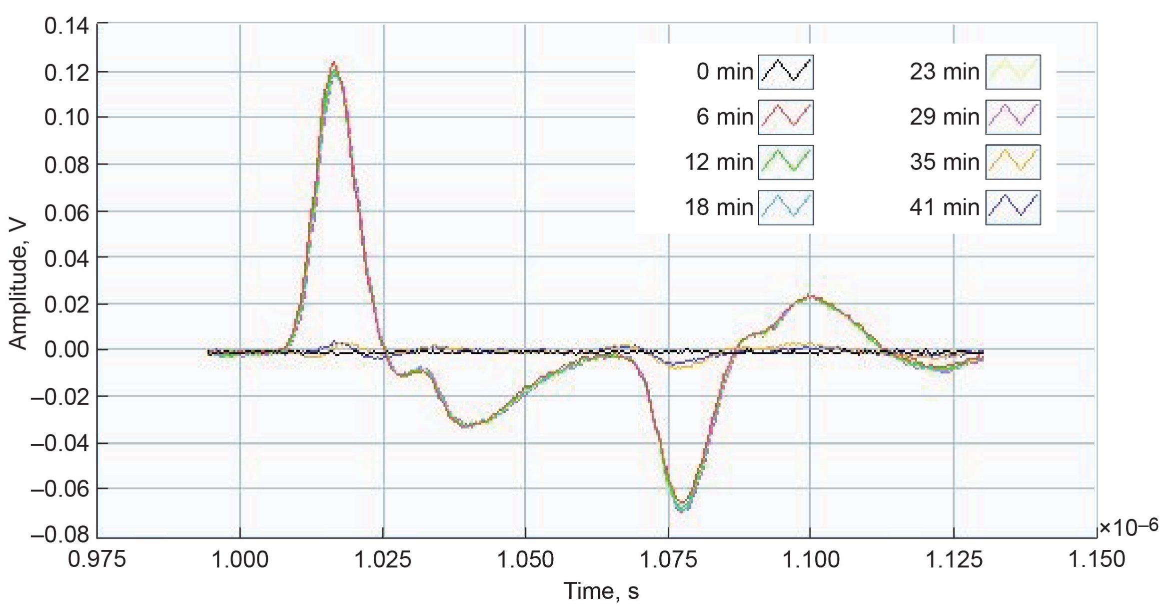


Figure 5.—PEA waveforms of 125-μm Kapton® film with a constant applied voltage of 9 kV.

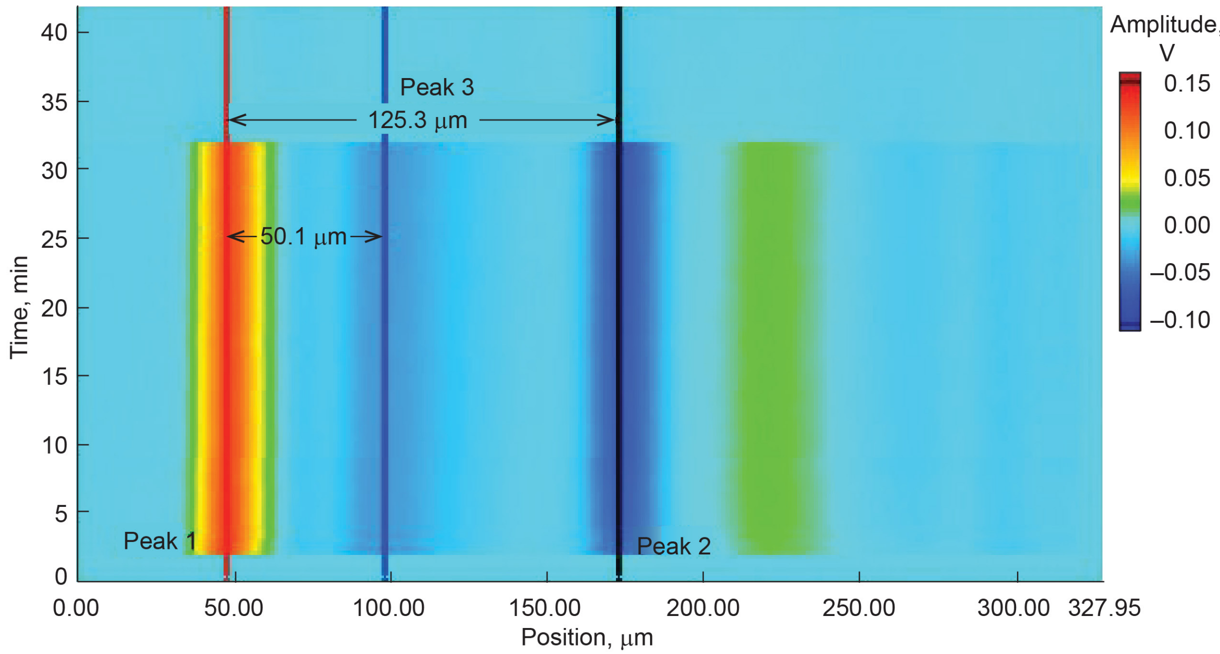


Figure 6.—Two-dimensional intensity map of PEA waveforms of 125-µm Kapton® film with a constant applied voltage of 9 kV over time.

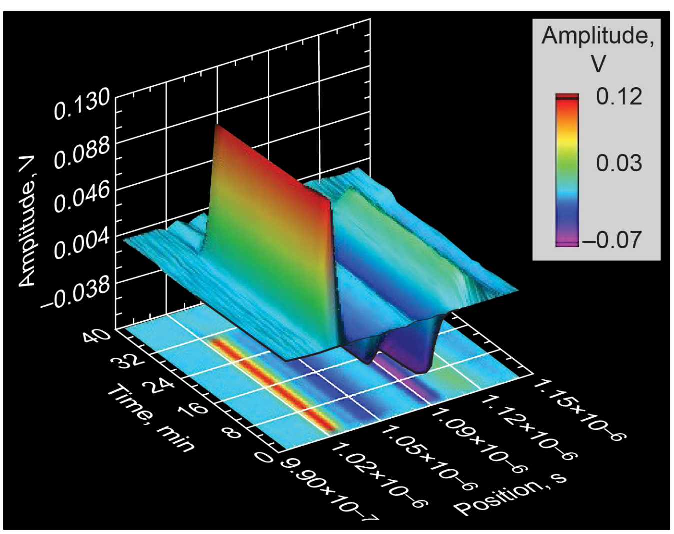


Figure 7.—Three-dimensional intensity map of PEA waveforms of 125-µm Kapton® film with a constant applied voltage over time.

The second Kapton® test was to evaluate a 125-µm Kapton® film under a varied voltage. This test applied increasing increments of 3, 6, 9, and then 0 kV for 10 min each. Figure 8 illustrates select waveforms throughout the 40-min test. The amplitude of the waveform peaks increases at each interval increase in voltage. However, the amplitude of the peaks at constant voltage decreases slowly over time, which suggests the charge accumulation is traveling through the sample. This behavior can also be illustrated by the negative embedded charge peaks shifting inward as time progresses. Figures 9 and 10 depict the two- and three-dimensional intensity maps of this test where the simultaneous increase in amplitude with voltage can be seen.

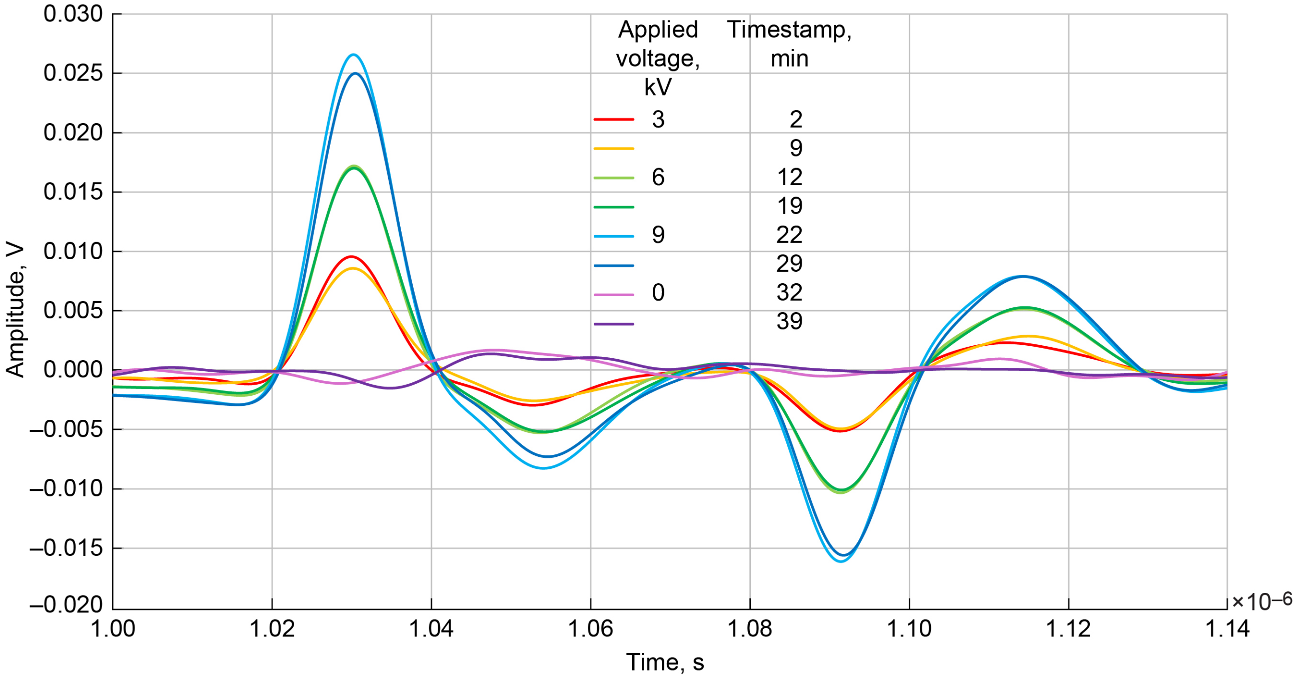


Figure 8.—PEA waveforms of 125-μm Kapton® film over various applied voltages at a series of timestamps from 2 to 39 min.

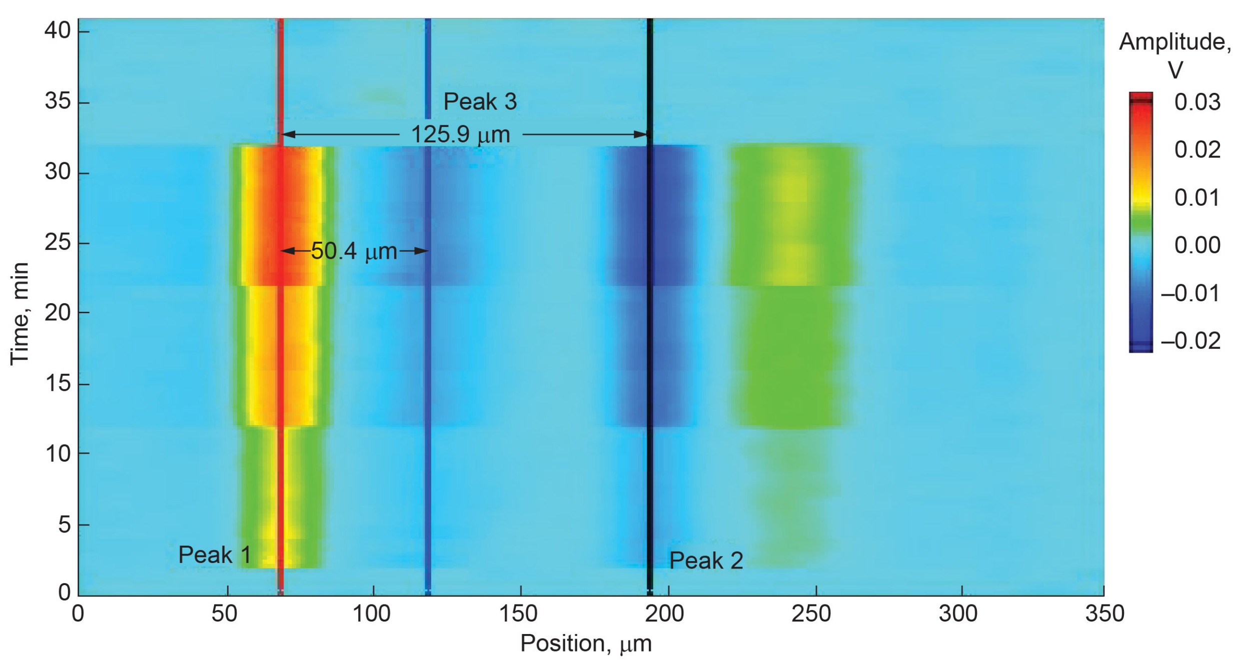


Figure 9.—Two-dimensional intensity map of PEA waveforms of 125-μm Kapton® film over variety of applied voltages: 0, 3, 6, and 9 kV, then back to 0 kV.

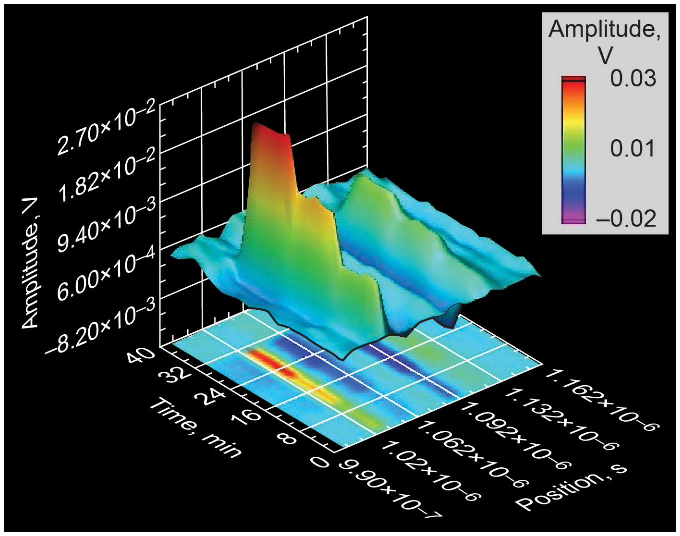


Figure 10.—Three-dimensional intensity map of PEA waveforms for 125-µm Kapton® film with variety of applied voltages: 0, 3, 6, and 9 kV, then back to 0 kV.

The last Kapton® test was to evaluate a simple multilayer system composed of two layers of 125-µm Kapton® film separated by oil to enhance contact. This test was identical to the second Kapton test where an increasing voltage in increments of 3, 6, 9, then 0 kV was applied to the sample for 10 min each for a total of 40 min. Figure 11 depicts a selected waveform at 6 kV at approximately 18 min into the test. The thickness of the sample can be seen to match the appropriate thickness measured from the waveform in Figure 11. Figures 12 and 13 illustrate the two and three-dimensional intensity maps of this multilayer test, respectively. The three-dimensional representation of this test best illustrates the charge migration through the two layers of Kapton® as shown by the decrease and then increase in peak intensity halfway through each voltage setting.

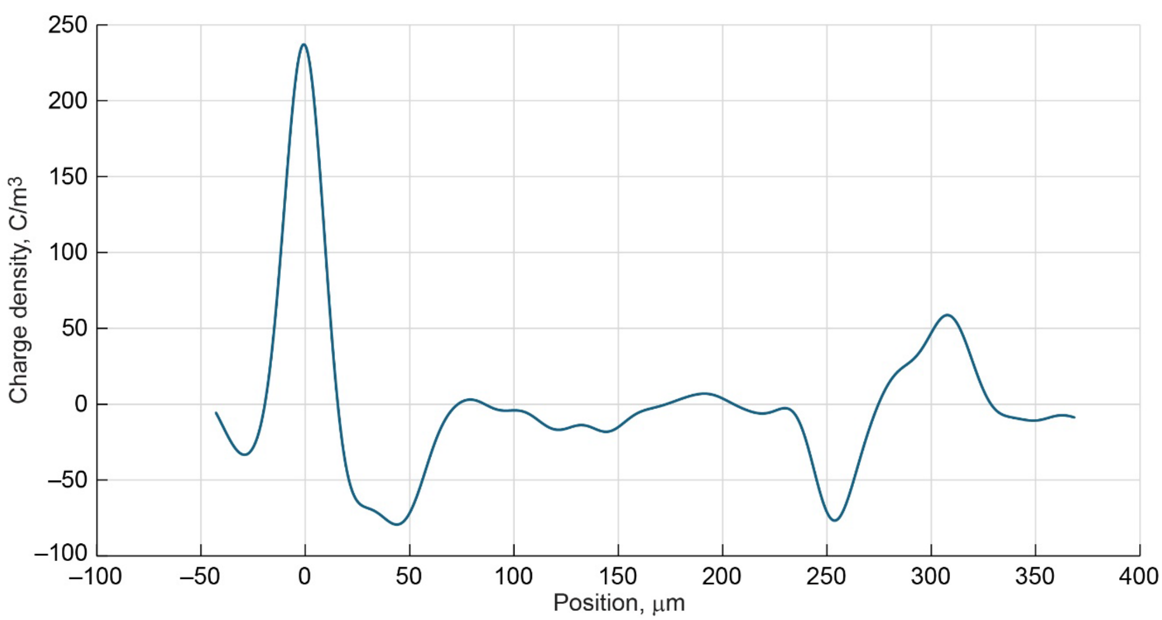


Figure 11.—PEA waveform of multilayer 250-µm Kapton® film at 6 kV.

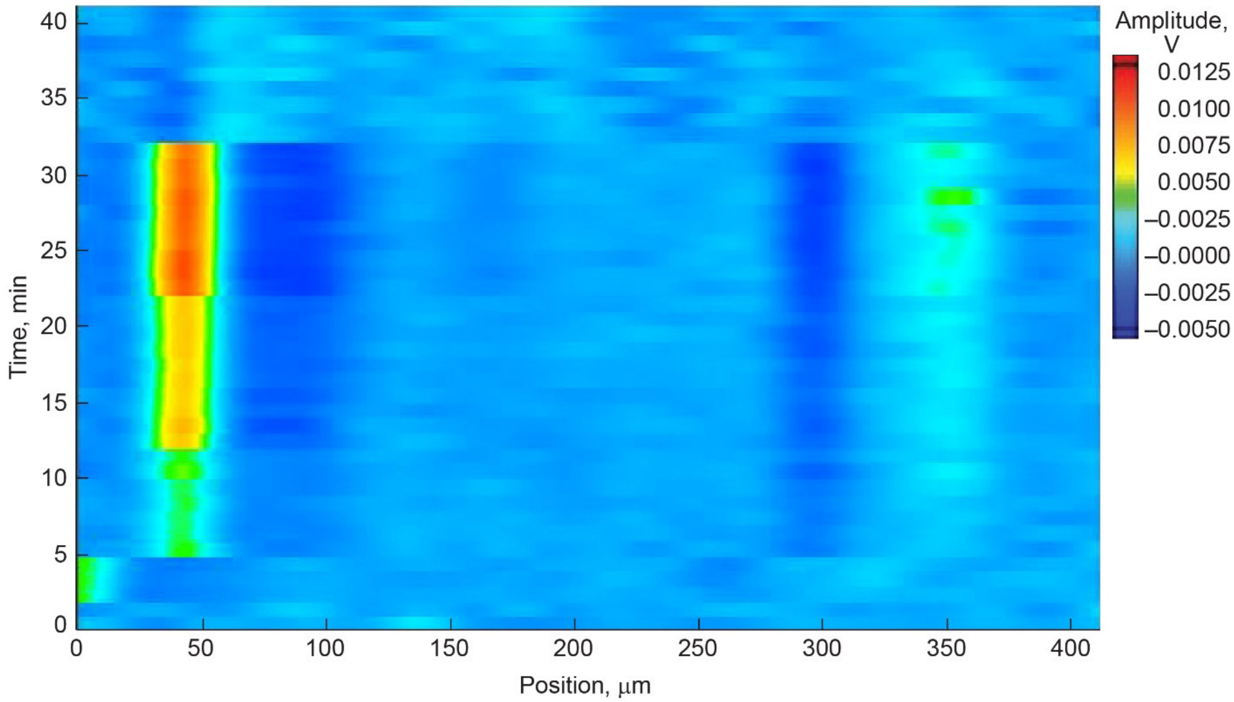


Figure 12.—Two-dimensional intensity map of PEA waveforms for multilayer 250-μm Kapton® film with variety of applied voltages: 0, 3, 6, and 9 kV, then back to 0 kV.

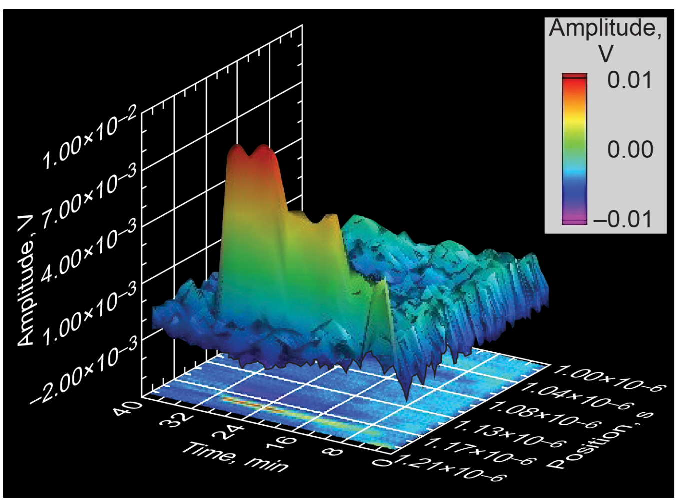


Figure 13.—Three-dimensional intensity map of PEA waveforms for multilayer 250-μm Kapton® film with variety of applied voltages: 0, 3, 6, and 9 kV, then back to 0 kV.

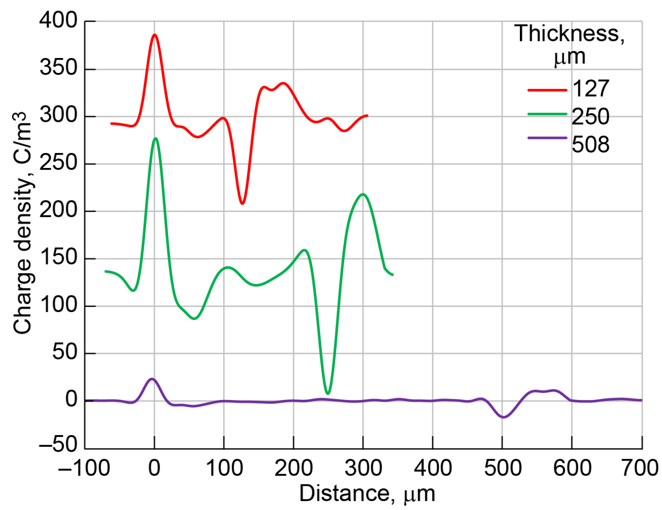


Figure 14.—Comparison of PEA waveforms at 9 kV for Ultem PEI films with varying thicknesses.

Next, samples composed of a PEI known as Ultem™ (SABIC) with varying thicknesses of 127, 250, and 508 μm were tested to illustrate their difference in performance. Each sample was tested under identical conditions of 9 kV applied voltage for 30 min and 0 kV applied voltage for 10 min. Figure 14 depicts a selected waveform at 9 kV for each sample and illustrates the difference in waveforms produced. Since the distance between electrode peaks corresponds with the thickness of the material, the thinner samples have shorter waveforms than the thicker samples. The thicker samples also show less charge accumulation peaks in their waveforms. Figure 15 depicts the three-dimensional intensity map of these tests.

Lastly, two samples of polyether ether ketone (PEEK) with varying thicknesses were tested to further detail the thickness dependency of insulation materials. A 100-μm- and a 250-μm-thick PEEK sample were tested under varying voltage conditions. The 100-μm PEEK film underwent 10-min increments

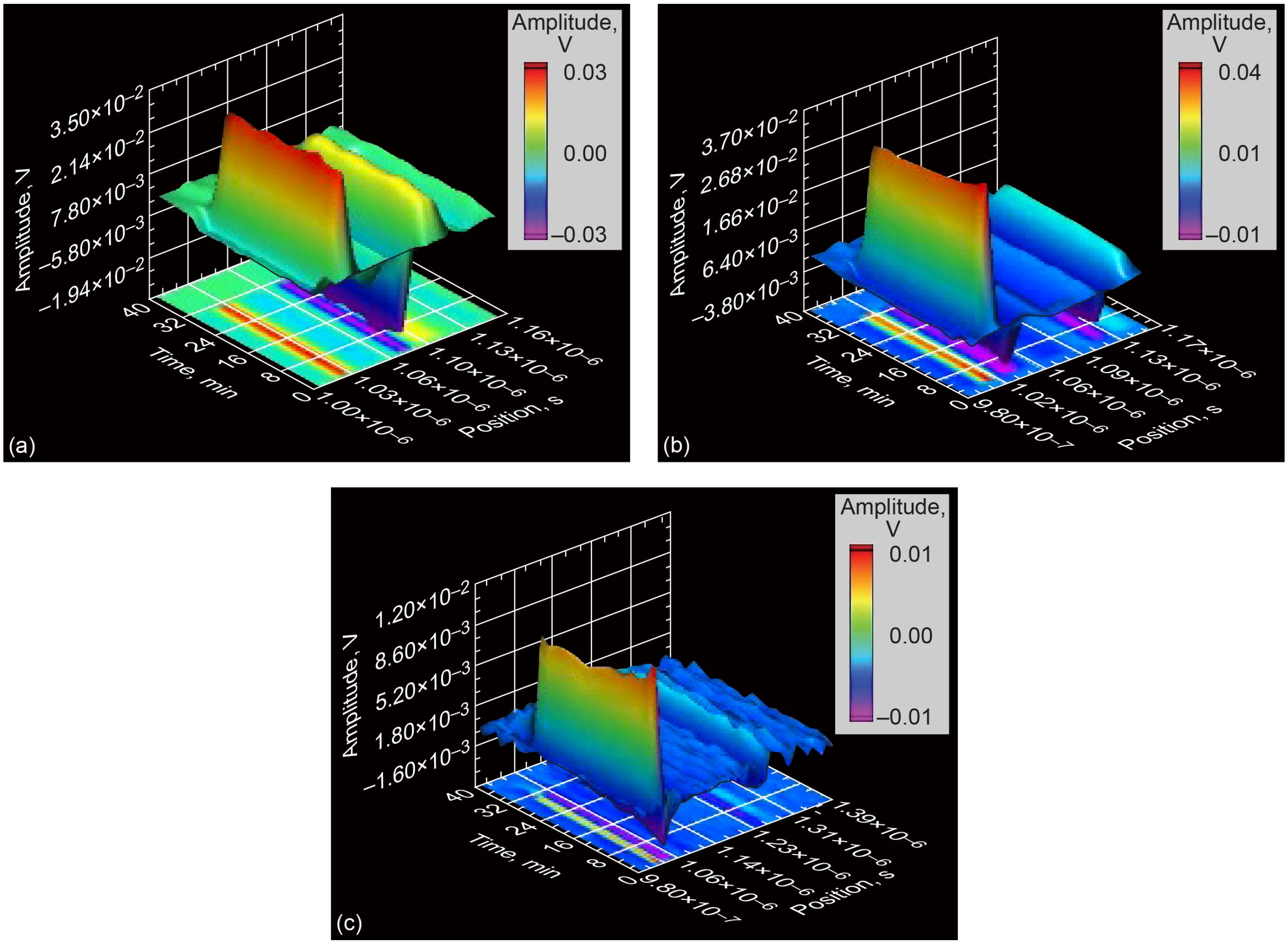


Figure 15.—Comparison of three-dimensional intensity map of PEA waveforms for Ultem PEI films at 9 kV with varying thicknesses. (a) 127 µm. (b) 250 µm. (c) 508 µm.

of 0.25, 0.5, 0.75, 1, and 0 kV applied voltages, and the 250-µm film underwent 10-min increments of 1, 2, 3, and 0 kV applied voltages. This difference from previous sample materials was due to the different dielectric breakdown strength of the PEEK films. According to technical data sheets (Ref. 14), PEEK has a dielectric withstand voltage of 16 kV/mm, meaning the thin sample can only withstand 1.6 kV, and the thicker sample can only withstand 4 kV before breakdown of the material occurs. Figure 16 depicts a comparison of a selected waveform at 1 and 3 kV for the thin and thick PEEK samples, respectively. Figure 17 depicts the three-dimensional intensity map of each of the PEEK tests. Ultimately, these tests showed that the thicker 250-µm sample depicted a more complex charge accumulation; however, additional tests will need to be completed at identical voltage conditions to verify the cause of the difference in charge accumulation.

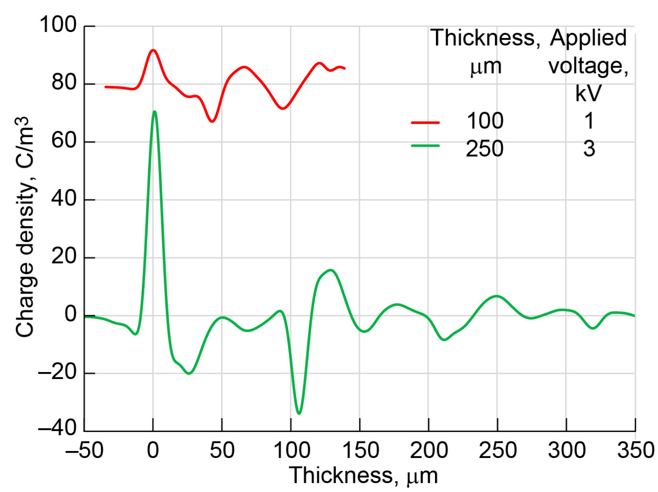


Figure 16.—Comparison PEA waveforms of PEEK films of varying thicknesses.

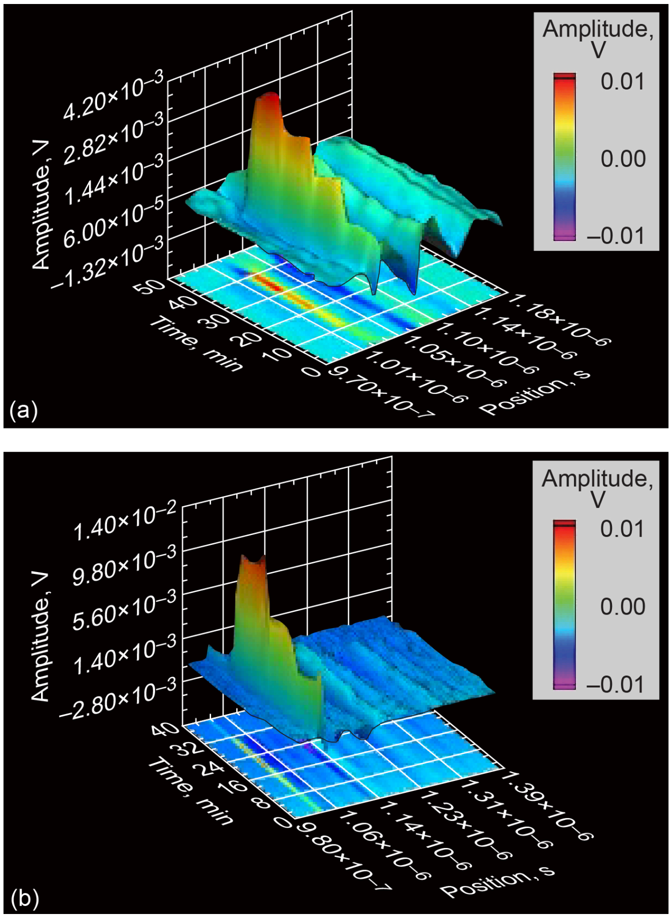


Figure 17.—Comparison of three-dimensional intensity map of PEA waveforms for PEEK films with varying thicknesses. (a) 100 μm at 0, 0.25, 0.5, 0.75, and 1 kV and then back to 0 kV. (b) 250 μm at 0, 1, 2, and 3 kV and then back to 0 kV.

Conclusions

In conclusion, pulsed electroacoustic (PEA) analysis is a nondestructive method for analyzing space charge accumulation and migration within dielectric materials. It is an important tool for evaluating materials under electrical stresses to identify optimal materials to be used in space and aeronautics electrical systems. Studying how materials perform under electrical stresses is a critical step in the prevention of failure of electrical components. This task established the pulsed electroacoustic analysis capability in Glenn Research Center's High Voltage Testing Laboratory by evaluating commercial polymer films. Films made of Kapton®, polyetherimide (PEI, Ultem), and polyether ether ketone (PEEK) were evaluated under various conditions. Kapton® has shown that charges accumulate within the samples; however, once a voltage is removed, the material relaxes quickly. Kapton® has also shown that by introducing an additional layer of material, less charge accumulation is detected. The PEA tests of PEI and PEEK indicated thicker samples are less affected by charge accumulation. These tests also served as benchmarks in establishing the types and thicknesses of materials the PEA system is able to analyze.

Future work will employ this PEA method to novel polymers and engineered composite materials. Multilayer composites will also be studied and compared with the multilayer modeling system within the PEA. These results will be coupled with additional High Voltage Testing Laboratory measurements such as dielectric withstand and breakdown voltages, surface roughness measurements, and thermal conductivity measurements.

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