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ELECTRETS AND THEIR APPLICATIONS IN CONTAMINATION STUDIES

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16. ABSTRACT

This report is a compilation of data on the surface charge of many different types of electrets formed by several different techniques. The report also includes some results on the investigation of electrets as pollution control devices for their possible use in the control of a spacecraft environment.

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ELECTRETS AND THEIR APPLICATIONS IN CONTAMINATION STUDIES

I. INTRODUCTION

Electrets have been known since the latter part of the 19th century. A substantial amount of work has been done on electrets, and a few practical applications, particularly in the area of communications equipment, have been made. In general, however, only qualitative descriptions of the various processes involved in electrets are known.

Electrets may be made in a variety of ways, but the method used most often in the past has been to make "thermoelectrets." A thermoelectret is made by placing a dielectric material between two electrodes, heating the dielectric material to near its softening point, then applying a high direct current field to the material between the electrodes. The field is maintained while the dielectric is cooled to room temperature; the electric field is then removed. If the treated dielectric exhibits electrical polarization, it is called an electret.

There are two conditions of the surface charge on electrets which have been given the names "heterocharge" and "homocharge." The term heterocharge refers to the surface charge on an electret which is of opposite polarity from the adjacent electrode, and homocharge refers to an electret surface charge of the same polarity as the adjacent electrode.

Electrets may be either heterocharged, homocharged, or mixed homo and hetero charged depending on the electret material, the method used in making the electret, the polarizing conditions, and the time elapsed since the electret was made.

The polarization processes involved in making electrets are:

a. The alignment of molecules within the dielectric having electric moments.

b. The separation of free charge carriers within the dielectric.

c. The deposition or injection of charges from outside the dielectric.

Any or all of these processes may be operating during the formation of the electret. The polarization processes which are internal to the dielectric give rise to heterocharge, while those from outside the dielectric give rise to homocharges.

An electret can undergo a change from a heterocharged to a homocharged condition. This effect occurs because of the relaxation of the internally induced polarization effects. The electret may also lose all polarization by simply heating the electret to a temperature near the forming temperature.

Since an electret when placed between the plates of a parallel plate capacitor gives rise to an induced current in the capacitor circuit, this effect is used to measure the surface charge of the electret. This report is a compilation of data on the surface charge of many different types of electrets formed by several different techniques. The report also includes some results on the investigation of electrets as pollution control devices for their possible use in the control of a spacecraft environment.

II. EXPERIMENTAL DETAILS

A. Thermoelectret Preparation by the Conventional Method

Thermoelectrets are usually prepared by a method developed by Eguchi [1], a pioneer in the field, with appropriate modifications depending on the material used for the sample preparation. The material to be polarized is melted or softened between two parallel high voltage (dc) electrodes for several hours. For the preparation of polymer thermoelectrets in this study, sheets of the various polymers were sandwiched between circular aluminum electrodes of the required size and then the assembly was kept in an electric oven for temperature and electrical treatment. A high voltage (dc) of several kV/cm thickness of the sample was applied for several hours under an elevated temperature. The sample was cooled down to room temperature under the same electric field. This process results in a redistribution of charges inside the material which will cause them to be "frozen in." The solidified sample when taken out of the electrode assembly will have electric fields on both surfaces. Although electrets can be prepared at low temperature, the magnitude of the charge and the life of the electret will be less than for the electret prepared at the molten state of the material [2,3,4]. The measurements of surface charge and surface field on both sides of the electrets were carried out at known intervals of time to study the decay characteristics of the polarized sample. A special measuring device was designed and developed to enable the transfer of charge by induction from the surface of the electret to a movable electrode and then to a Keithley 610B electrometer. In this device the entire measuring system was kept under shielded conditions to eliminate all the stray charges and also to avoid all electrostatic disturbances. For the surface field measurement, another field measuring device was designed and developed. An Isoprobe Electrostatic voltmeter (Model 144S-1) with a measuring probe manufactured by Monroe Electronics was used for surface field studies on both sides of the electrets. Usually the surface charge and field of a polarized sample were measured for several weeks to study the decay mode and persistence of charge.

B. Thermoelectret Preparation by Charge Injection Method

The conventional method of making thermoelectrets is usually very slow. It is also difficult to produce electrets of large size and complexity by this method. A novel method has been developed for the rapid production of electrets of large area and any

suitable shape. In this method, a dielectric sheet is continuously passed through an oven maintained at an appropriate temperature. When the heated sheet emerges, a corona discharge is induced over the surface of the dielectric by applying a high voltage direct current potential to a metal wire brush or a series of thin wire electrodes kept a short distance from the dielectric. This process thus allows charge injection on the dielectric and, consequently, polarization of the material. The moving dielectric with induced polarization now passes through a grounded air-cooled or water-cooled metallic plate. The injected and oriented charge in the dielectric is thus frozen in, and the resultant material has now formed an electret of superior characteristics to the previously reported types of electrets. Usually electrets of opposing polarities may be produced on opposite sides of the dielectric sheet. The surface charge and surface field studies of these samples can also be done by the method previously discussed.

C. Preparation of Electrets by Charging with a Tesla Coil

In this method, the heated dielectric sheet is charged with a high frequency ac potential derived from a Tesla coil. The charged sample is then cooled down to room temperature by passing it over a cool grounded metal plate. The solidified dielectric sheet exhibits reasonably good charged samples. The measurements are carried out as discussed in the previous cases.

D. An Alternate Method of Producing Electrets of a Material

In this method, the molten dielectric is sprayed through a corona discharge maintained between the spray gun and a cool surface. The thin layer of dielectric mist collected over the cool surface is found to exhibit a surface charge similar to those reported in the earlier sections.

III. MATERIALS USED IN THIS INVESTIGATION

Polymers are found to exhibit good electret properties with stable surface charges even in humid surroundings [5-8]. The thermoelectret properties of the following polymers are reported in this study: Teflon, Polycarbonate, Polyethylene, Polypropylene, metal-impregnated Kapton, Plexiglass, and fiberglass coated with Teflon. Although some of these materials are found to exhibit excellent electret properties, they cannot be used under extreme temperature conditions, particularly under high temperature surroundings. Therefore, a few other inorganic materials which may withstand high temperature, humidity, pressure, etc., have been investigated. Thermoelectrets of mica, gadolinium molybdate, and fused quartz were found to be suitable materials for electret preparation under suitable conditions of polarization. In addition to these materials, liquid crystals, such as cholesteryl nonanoate, have been found to exhibit the electret effect.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Teflon Electrets

The surface charge decay characteristics of Teflon electrets prepared by the various techniques discussed in Section II are shown in Figures 1 through 15. The electrets prepared by the conventional method usually show a pulsatory nature of decay of charge, at times with charge reversal as indicated in Figures 11 and 12. The magnitude of charge, the type of charge (hetero or homo), the irregularity in the decay mode, the charge reversal, etc., are found to be dependent on the material of the electret and the polarizing conditions. The charge decay properties of three layers of 0.125 mm thick Teflon samples prepared at 225°C temperature with a polarizing field of 200 kV/cm for 6 hours are shown in Figure 15. Layer 1 was in contact with the anode of the high voltage dc supply, while layer 3 was in contact with the cathode and layer 2 was sandwiched between layers 1 and 3. Although all three samples were polarized under identical conditions, the polarization properties, and consequently the charge decay characteristics, are found to be different depending on the placement of the sample with respect to the electrode system. For layer 1, anode and cathode show the same positive charge. The second layer, which did not have any direct contact, shows hetero and homo charge on opposite sides with a charge reversal on the cathode side. The third layer shows only homo charge formation. The magnitude of the charge in each case is also found to be different. Figures 14 and 15 show the surface charge decay with time of 5 layers of 0.125 mm thick Teflon samples prepared at 250°C polarizing temperature with 200 kV/cm polarizing field for 6.5 hours of polarization time. As in the three-layer system of electrets, the charge formation and decay of each layer is found to be different depending on the position of the layer in the electrode assembly. Although identical results are not obtained in each layer, these results show that multilayer electrets can be formed simultaneously and that the intermediate layers, in general, will have only volume polarization because they are shielded from the electrodes by the first and last layers and, consequently, spray charge from the electrode under high voltage conditions can be avoided. Figure 10 shows the characteristics of volume-polarized, two-layer Teflon electrets. These electrets have only typical heterocharge since the field of 15 kV/cm was probably insufficient to spray enough charge from the electrodes to produce an effective resultant homocharge. Thus, these studies show that, depending upon the need, suitable polarization conditions can be used so that a particular type of charge can be ultimately obtained by suitably adjusting the polarizing field, temperature, time, thickness of the sample, and the electrode material.

Figures 1, 2, 4, 8, and 9 show the surface charge decay characteristics of Teflon electrets formed with corona charging using the charge-injection previously described. The results obtained by corona charging at an elevated temperature with appropriate polarizing voltage are found to be very effective and useful in inducing polarization in various types of dielectrics. Once charged by this method, the dielectric usually produces homocharge for low polarizing voltage and heterocharge for higher values of polarizing

voltages. Interestingly, the samples have almost constant charge without any appreciable decay with time as in the case of thermoelectrets prepared by the conventional method. Also the magnitude of the charge in this case is found to be considerably higher than the electrets prepared by the conventional method. It is faster and relatively simple to fabricate; any size, shape, and thickness can be obtained. In certain cases, as shown in Figures 8 and 9, surface charges of approximately 10^{-6} C/cm^2 were obtained initially, but these high charge densities cannot be maintained under the usual laboratory atmospheric conditions because of humidity, ionization, and leakage in the surroundings. However, even after the decay, charges of approximately 10^{-8} C/cm^2 were always retained and were greater than the thermoelectret charges obtained by the conventional method. The magnitude of charge as well as the other characteristics are found to depend on the number of times the dielectric is sequentially charged. Therefore, for higher charge density, better stability, longer life, and an economical and easier method of making electrets of desired types of charge and shape, this newly developed method is certainly superior to the other well-established methods.

Figures 5, 6, and 7 show the surface charge decay properties of electrets prepared by the method of charging using a high frequency ac supply from a Tesla coil. The magnitude of the charge and the decay mode of the resultant polarized Teflon sheets are found to depend on the charging pattern, forming temperature, and charging voltage on the Tesla coil. The upper side on which the charging took place always has a positive charge, and the lower side has a negative charge similar to a thermoelectret. Although the magnitude of charge and the stability and life of these types of charged sheets are comparatively poorer than the brush corona charged sample, the results are encouraging. By improvements in the manufacturing method it may be possible to obtain results at least similar to the thermoelectrets obtained by the conventional method of fabricating electrets. Therefore, this method may be superior to the conventional method.

Figure 3 shows the interesting characteristics of two electrets prepared by allowing a plastic spray (3M brand "77" adhesive) to pass through a brush corona charge onto a Teflon substrate. After solidification, the peeled-off, sprayed sheets have the characteristics shown in the figure. When the plastic spray mist passes through the positive ions of the brush corona, the particles acquire similar charges. When these particles form a layer over a cool surface, the upper surface is found to have the charge of the ions, and the other surface, because of a charge compensation technique, has an opposite charge, thereby forming a typical thermoelectret with heterocharge formation. However, these initial results must be substantiated by more extensive experimentation. This method may be useful and effective in electret preparation. The method has an added advantage since by having ions of the desired charge it is possible to obtain the same type of charge on any surface. Hence, for many types of practical applications, charging with the spray gun may be advantageous over the methods previously mentioned.

B. Polyethylene Thermoelectrets

The surface charge decay characteristics of polyethylene thermoelectrets prepared by the various methods are shown in Figures 16 through 24. The decay curves with time shown in Figures 19 through 22 are those corresponding to the thermoelectrets prepared under different polarizing conditions, particularly by varying the polarizing field from 5.5 to 90 kV/cm. Up to a 15 kV/cm field all the samples show homocharge on both sides without any charge reversal as shown in Figures 22 and 23. For higher fields in certain cases (Fig. 20), the intial homocharge is reversed to a final heterocharge state, which is an unusual behavior. For higher fields, still more complicated, unpredictable behavior is shown (Figs. 19 and 20). Charge decay properties of brush corona charged polyethylene electrets are shown in Figures 16, 17, 18, and 24. Once again, as in the case of Teflon electrets, samples prepared by the corona charging technique are found to be much better in obtaining high charge magnitude without any reversal or appreciable decay with time. Therefore, for various practical applications, particularly for temperatures up to 100°C, this material is recommended. Tesla coil charged samples are shown in Figure 23. Heterocharged electrets are obtained in this case, but their magnitude and stability are not found to be as good as the other samples.

C. Polyproylene Thermoelectrets

Polypropylene is an interesting polymer with excellent dielectric and mechanical properties similar to those of Teflon. It can be used for applications which may have high temperature surroundings up to approximately 160°C. A series of thermoelectrets was prepared by varying the polarizing field and temperature to study the polarization properties of this polymer. The results are shown in Figures 25 through 32. In all these cases the samples were shielded by interposing thin mica sheets between the electrodes and the sample surface. This technique was used to avoid external polarization in the sample so that only volume polarization and, consequently, charge of the heterocharge type would be obtained in the resultant sample. This study, again, shows that charge of only one type can be obtained without any charge reversal and irregular decay if thermoelectrets are prepared by this method. In this case, the surface voltages measured 2 mm from the sample surface were also recorded at known intervals of time, and a few typical results are presented in Figures 25 through 32. There was, however, some limitation in measuring the maximum surface voltage because the instrument used was capable of measuring only 2000 volts. In many cases the voltages observed were much more than 2000 volts. The surface voltage decay also follows the same pattern as the surface charge decay characteristics of the same sample. The characteristics of the brush corona charged samples and Tesla coil charged samples at elevated temperature are shown in Figures 29 through 32. A maximum of 10^{-6} C/cm^2 charge was obtained with high stability in the sample prepared with 10 repeated chargings of 14.5 kV at 2 mm from the sample at 100°C. However, the results in Figure 32 indicate that charging the same surface more than 10 times deteriorates the polarization and, consequently, reduces the magnitude of the surface charge and also causes an irregular decay. Hence, it is appropriate to find suitable polarizing conditions for each type of material.

D. Thermoelectret Properties of Plexiglass

In this section another interesting material, polymethylmethacrylate (plexiglass), was used for electret formation. Thermoelectrets prepared by the conventional method show single or, in certain cases, double reversal and irregular decay characteristics (Figs. 33 and 34). Therefore, a decision was made to shield the spray charge from the electrodes by keeping the samples sandwiched between mica sheets before applying the field. The results shown in Figures 35 and 36 exhibit only one type of charge, and the stability is found to be better than the results shown in Figures 33 and 34. Figure 37 shows the charge decay of two samples charged with a Tesla coil at 30°C and 185°C. These results show that charging by other techniques is also possible with this material; however, the magnitude of charge obtained in this case and the stability of the electrets are inferior when compared to the properties of Teflon and polypropylene electrets.

E. Thermoelectrets of Metal-Impregnated Kapton

A metal-impregnated, double-polymer Kapton product has been developed at the Marshall Space Flight Center for use as a flat conductor for making electrical connections in space vehicles. The Dupont product Kapton is made from polyimide/fluorinated ethylene propylene. Polyimide is coated only on one side of the flat metal conductors and the other side is coated with heat sealable fluorocarbon resin 0.005 cm (0.002 in.) thick. In this section the electret forming properties of Kapton are briefly discussed. The results of electrets prepared by the conventional method with mica for shielding purposes on both sides of the samples under various conditions of polarization are given in Figures 38 through 43. The results obtained are comparable with any of the better known electret materials. The samples contained eight flat metal electrodes sandwiched in parallel arrangement with approximately 2 mm spacing between electrodes. When charge distribution over the surface of the electret is required to be nonuniform this method can be suitably adapted for electret preparation. It has added mechanical strength since metal strips are incorporated in the samples. Also, it is possible to produce negative and positive charges on the same surface by alternately connecting the flat copper strip to the positive and negative electrodes of the forming voltage. These types of electrets are reported here for the first time, and the mechanism of electret formation in this case and the theoretical interpretation of the results require further extensive systematic investigation.

F. Thermoelectret Properties of Other Materials

In this section preliminary results on the thermoelectret characteristics of a few other important materials are presented. Most of the materials previously discussed cannot be used under temperature conditions higher than approximately 200°C. At high temperatures these polymers lose their charge as molecular reorientation due to thermal agitation takes place. However, the materials reported here (mica, fused quartz, etc.) have

extremely good mechanical properties. They can also withstand very high temperatures. Therefore, a decision was made to determine if these materials could be electrified with reasonable surface charge characteristics. The results are encouraging and important from a practical application point of view.

1. Mica Electrets. The dielectric and electric properties of mica are well known. Figure 44 shows the charge decay characteristics of two mica electrets prepared with 7.7 and 14 kV polarizing voltage at 160°C for 8 hours. It was observed that even at this low temperature, well below the melting point, reasonable charge could be obtained. The charge formation characteristics of mica sheets are considerably improved by the brush corona charging technique (Fig. 45). However, these results can be improved further by improving the polarization conditions, particularly under high temperature.

2. Mylar Electrets. One-side, metal-coated Mylar foil of 0.08-mm thickness was used in this case. Brush corona charging and Tesla coil charging are found to induce polarization in this material with charge of opposite sign on opposing sides. However, the magnitude of charge obtained in this case was smaller as the sample was polarized only at room temperature conditions. Therefore, it is necessary to improve the method of fabrication because Mylar is one of the best polymers available for practical applications (Fig. 46).

3. Thermoelectrets of Quartz. Single crystals of quartz and fused quartz discs were used for polarization investigations. It was found that fused quartz and single crystals can be polarized under suitable conditions of polarization. It was suggested that the polarized quartz may perform better when used in certain practical applications, particularly in Quartz Crystal Microbalance (QCM) work for contamination studies. Some of the typical results are shown in Figure 47.

4. Polycarbonate Thermoelectrets. Polycarbonate has very good electret characteristics. Typical results obtained by brush corona charged polycarbonate samples are shown in Figure 48. After charging, an initial charge of approximately 10^{-5} C/cm^2 was obtained in this material which is the highest surface charge value of an electret ever reported. However, it is not possible to retain this much charge under ordinary atmospheric conditions and, consequently, the initial decay was fast until it reached a value of 10^{-8} C/cm^2, and thereafter it continued to be stable as in Teflon and other materials. Therefore, this material can also be used effectively, particularly when the application requires temperatures below approximately 100°C.

5. Teflon Coated Fiber Glass Electrets. Fiber glass made in the form of a flexible woven sheet, coated with a thin coat of Teflon on both sides is proposed for lining the inner wall of the cargo bay and other portions of the Space Shuttle. This material has innumerable holes in it similar to a woven cloth. For contamination control in the Space Shuttle and other space vehicles, this material may be a potential candidate. Therefore, experiments were performed with this material also, and the results are encouraging. The preliminary results obtained in a few typical cases with brush corona charged samples are

shown in Figure 49. Anode and cathode produce the same type of charge except for one reversal in one case. This may be due to the penetration of charge of the brush corona through the innumerable holes present in the material so that the lower side receives the same type of charge. However, it may be possible to make fabrication improvements necessary for practical applications. It may also be necessary to improve the polarization by proper modifications of the technique to obtain a higher magnitude of charge with longer life and stability.

6. Thermoelectrets of Gadolinium Molybdate (GMO) Single Crystal. In the previous sections thermoelectret characteristics of various types of polymers and other dielectrics have been discussed. These materials are of questionable structure and purity, and the physical and chemical properties vary considerably from sample to sample; therefore, it is very difficult to predict their behavior. Consequently, quantitative analysis and a scientific understanding of the mechanism of polarization in these materials are extremely difficult to achieve. It was thought to be appropriate to extend the electret study to a single crystal of well-known purity and well-defined structure. Gadolinium molybdate was selected for this purpose. It is a ferroelectric-ferroelastic type of material. It was assumed that the spontaneous polarization of the single crystal of GMO could be enhanced considerably by inducing polarization by electret formation at or near the Curie temperature of the material. It has a Curie point of 159°C and a spontaneous polarization of 0.17 $\mu C/cm^2$ at room temperature. Figure 50 shows the charge decay characteristics of a GMO single crystal electret formed with a polarization field of 75 kV/cm at 165°C, which is slightly above the Curie temperature, and with a polarizing time of 5 hours. The anode side and the cathode side show reasonably high homocharge of approximately 10^{-8} C/cm^2 initially. But the homocharge on both sides was found to reverse in a few days to a heterocharge which developed to a maximum value. In a few days the heterocharge again started reversing to a homocharge. Observation of the decay characteristics of this sample shows that during a period of approximately 36 days the charge reversal took place four times, as indicated in Figure 50. This multiple reversal and electret formation in a single crystal are reported here for the first time. The multiple reversal may be due to the superposition of the volume polarization, spontaneous polarization, and the external polarization from the high voltage electrodes. As the relaxation time of each of these components varies considerably, multiple reversal phenomena of the type observed here are possible. However, it would be useful if polarization of one type alone could be obtained in a single crystal electret. Therefore, thin mica sheets were interposed between the crystal and the high voltage electrodes at the time of formation of the electret. As expected, the samples prepared in this fashion showed only one type of polarization, as shown in Figures 51 through 54. The decay rate seems to be faster than other materials, probably because of the rapid reorientation of the aligned domains. By increasing the polarization time, field, and temperature, the magnitude of the charge and the stability improve appreciably as shown in Figure 54. Charge decay characteristics of a corona-charged, GMO single crystal are shown in Figure 55. This sample was charged 20 times with a 15-kV polarizing voltage on the corona electrode at 168°C. The crystal acquired a large amount of homocharge on both sides

and the stability was also found to be better. For comparison, characteristics of a corona-charged Teflon electret made under identical conditions are also shown in Figure 56. These studies indicate that it is possible to induce adequate amounts of polarization in single crystals of known structure and properties. With further work in this direction it is hoped that useful scientific information can be obtained which may help to explain the polarization mechanism. Furthermore, this technique of inducing artificial polarization in single crystals may help in changing the electrical, mechanical, and dielectric properties of these materials. Therefore, it may be possible to have useful applications of single crystal electrets in practical devices.

V. APPLICATIONS OF ELECTRETS AS APPLIED TO CONTAMINATION STUDIES

Electrets are now used in many practical devices, particularly in electrostatic measuring instruments, high-voltage generators, ionography, xerography, electrothermography, electrostatic recording, memory elements, microphones, transducers, radiation dosimeters, and prosthetic devices. It has also been proposed that electrets be used in air pollution studies. In this section, the applications of electrets in the detection and control of gaseous and particulate matter as developed by the authors are reported. Also, some details of the application of polymer electrets in the detection and analysis of rocket exhaust effluents are presented. Electrets are desirable because of their small size, light weight, long life, and low cost of manufacturing. They can be effectively used as a source of stable electrostatic field in any device, particularly in remote locations such as oceans, mountain tops, or in space.

A. Electrets for the Study of Organic Vapors and Gases

It was found during this investigation that thermoelectrets of polymers with stable surface charge on both sides are suitable devices for attracting and collecting charged particles and ions to their surfaces and holding them for a very long time. It is also possible to induce charges of opposite sign on neutral particles and attract them to the surface of the electret. Therefore, a decision was made to undertake a systematic study of the use of electrets in collecting various types of organic vapors from acetone, alcohol, benzene, carbon tetrachloride, xylene, etc., and also gases such as CO_2 and SO_2. Thermoelectrets of Teflon, polycarbonate, and other polymers with stable surface charge characteristics were used for this purpose. The gaseous contamination collection properties of electrets were evaluated by mass spectral analysis of the exposed sample.

Portions of the foil electret samples of approximately 1 cm length and 0.1 cm width were cut and exposed to vapors coming from different contaminants under various experimental conditions. Mass spectra of the unexposed as well as the exposed samples

were taken systematically by using the solid sample probe of a Varian M-66 cycloidal mass spectrometer. The electron energy from the electron gun was kept at a constant value of 70 eV for ionizing vapors from the sample probe. The ion source and the analyzer of the mass spectrometer were kept at constant temperatures with the vacuum operated within limits of 10^{-6} to 10^{-7} torr so that stable mass spectra could be obtained.

Figure 57 is the mass spectrum of the SO_2 collected by a Teflon electret showing the characteristic peaks at 64 and 48 AMU. Figure 58 shows the mass spectra of acetone and xylene vapors as the sample was exposed to an equal mixture of these two liquids. Mass spectra of the mixed vapors collected on Teflon electrets from equal proportions of the liquids acetone, alcohol, benzene, carbontetrachloride, and xylene are shown in Figure 59 at probe temperatures of 45°C and 100°C. Electrets of Mylar, polycarbonate, unpolarized polycarbonate, and aluminum foil were also used. Examples of the polycarbonate (both polarized and unpolarized), polarized Mylar, and aluminum foil exposed in an atmosphere with SO_2 gas are shown in Figures 60, 61, and 62. The results show that an electret is more effective than the metal foil or unpolarized polymers in collecting vapors and gas contaminants. The unpolarized polycarbonate sheet had a small amount of surface charge before it was exposed to the contaminants and, therefore, was expected to show relatively small peaks as shown in Figure 61. The results of a series of experiments show that concentration of the collected pollutants increases linearly with increase of exposure time as shown in Figure 63.

These investigations show that electrets are very efficient devices for collecting, detecting, and controlling various types of pollutants and also that the mass spectrometric technique is an effective method in analyzing these contaminants. Also, the handling of the sample is relatively simple and no special treatment is required before the actual analysis of the sample.

B. Rocket Exhaust Effluent Studies by Thermoelectrets

Thermoelectrets made of Teflon were used to collect rocket exhaust products. The exposed electrets were then studied by scanning electron microscopic and X-ray microprobe analysis. It was possible by these studies to identify the various effluents coming out of the rockets at the time of firing. A typical SCM photograph is shown in Figure 64. Figure 65 shows the X-ray microprobe intensity spectra of the various exhaust products collected on the Teflon electrets. A series of experiments was conducted to study the rocket exhaust effluents from the 6.4 percent Space Shuttle Vehicle (SSV) at the Marshall Space Flight Center test facility. A typical computer printout of the X-ray microprobe analysis of the various products collected on Teflon electrets is shown in Table 1. Direct comparisons were made with the results obtained from a millipore filter and bubbler for samples kept under identical conditions. This helped in calibrating the intensity of the X-ray spectra with respect to the concentration of the products collected

on electret surfaces. These comparisons show a high degree of consistency of the results. This method, therefore, can be employed to great advantage in obtaining the entire spectra of the pollutants coming out of the rocket. Other methods employed showed only the concentration of HCl. However, more extensive investigations must be performed to obtain quantitative results with electrets.

C. Dust Collection Properties of Electrets

Electrets are found to be excellent devices for collecting dust and particulate charged or uncharged matter. Electrets when exposed to a laboratory atmosphere were found to have collected large quantities of particles of different sizes and shapes. Two identical cylinders, one with and one without an electret lining, were fitted on a rectangular chamber with an exhaust fan on one side of it. Clear, dust-free, 2.54 cm (1 in.) diameter fused quartz discs were placed in both cylinders, and the cylinders were exposed to the laboratory atmosphere for several hours. After several days, both discs were taken out for measurements. The particle size and number on the surface of both the discs were scanned by means of an optical microscope and an automatic particle counting system. The counting instrument, the OMNICON, scans the electret and automatically sorts the particles by size and measures the maximum horizontal chord of the particles. The oversize count feature of the OMNICON is utilized to carry out the counting process. The program steps through an array containing the micrometer sizes to be searched for across the field of view.

The size is taken from the array, and a count of all the particles having a maximum horizontal chord greater than this size is made and stored. The next successive size is then taken from the array and a count of all the particles having a maximum horizontal chord greater than this new size is made and stored. The program continues through the size-range array until a count for all sizes has been made. To determine the number of particles present having a particular size, the difference between counts for successive sizes is calculated. Table 2 shows the typical particle distribution obtained on a Teflon electret. Figure 66 shows photographs of electret surfaces with dust collected on them. Figures 67 through 70 show the particles collected on quartz discs placed in identical cylinders of 25.4 cm (10 in.) diameter and 11.4 cm (4.5 in.) height with and without electret linings. It can be seen that the sample placed in the cylinder with the electret lining collected only a few particles when compared to the one placed in the cylinder without any electret lining. For a detailed study, a flow meter with electret filter is being designed and developed. The results obtained in this part of the investigation, however, show that electrets can be used effectively in collecting and controlling particulate matter, dust, and microorganisms, and will screen liquid and solid impurities that are suspended in the air.

VI. CONCLUSION

The salient conclusions of these investigations are summarized as follows:

1. The electret effect in a number of dielectrics such as Teflon, polyethylene, polypropylene, plexiglass, metal-impregnated Kapton, polycarbonates, etc., has been obtained. However, for practical applications up to about 200°C a Teflon electret is found to be most useable because it shows better stability and charge retention.

2. Three new techniques to induce a high degree of polarization in polymers and other dielectrics have been reported for the first time. These methods have many advantages over the conventional method of electret fabrication because it is possible by these techniques to produce an electret of any size and shape within a very short time. The characteristics of these types of electrets are also better than the electrets reported by other methods. Out of the three methods, brush corona charging is found to be the best method for obtaining uniform charge distribution.

3. An initial charge of approximately 10^{-5} C/cm^2 has been reported for the first time.

4. Mica and fused quartz could be polarized even at low temperature conditions. Electrets of these materials can, therefore, be effectively used under extreme conditions of temperature, pressure, and humidity.

5. Metal-impregnated Kapton is found to exhibit excellent electret properties. This result is reported for the first time. When polymers of better physical strength and uneven charge distribution or even positive and negative charge of varying magnitudes are required, the metal-impregnated electrets can be used advantageously.

6. It has been reported, for the first time, that single crystals like GMO can be polarized under suitable conditions. To understand the mechanisms of polarization in dielectrics, this type of study would be beneficial.

7. Thermoelectrets of polymers could be successfully used in detecting and controlling contaminants in the form of particulate matter and gases. Mass spectrometric analysis has been employed in studying the pollution collected over the surface of electrets, and this technique is a powerful tool in such studies. This type of application of electret and analysis has been accomplished here for the first time.

8. Dust and particle collection properties of electrets show many promising applications.

9. Thermoelectrets of polymers were used successfully for the first time in collecting rocket exhaust effluents. SCM and X-ray microprobe analysis show very interesting and important results. This method has the added advantage of obtaining the entire spectrum of pollutants from a rocket exhaust and, as such, it can be considered as a powerful tool in studying contaminants of these types.

NOTE: The absolute value of the magnitude of polarization reported in these studies may be obtained by multiplying the reported values by 1.18. This was necessary because of the difference in the size of the measuring electrode from unit area and also because of the distance between the surface of the electret and the induction electrode.

TABLE 1. TYPICAL COMPUTER PRINTOUT OF THE X-RAY MICROPROBE ANALYSIS OF THE ROCKET EXHAUST EFFLUENTS COLLECTED ON TEFLON ELECTRETS

keV	Counts	Elements
.693	11086.	# Fe
1.528	113227.	# Al
1.752	428721.	# Si
2.146	8639.	# Au
2.316	33394.	# S
2.644	20258.	# Cl
3.387	5830.	# K
3.699	1863.	# Ca
4.490	204.	# Ti
5.438	4628.	# Cr
5.948	728.	# Cr
6.430	14415.	# Fe
7.086	1528.	Fe
7.494	2611.	# N
.400		#
.486		#
.710	11343.	# F
1.000	3103.	# Cu
1.510	229375.	# Al
1.766	187184.	# Si
2.119	3215.	# Au
2.328	9320.	# S
2.653	16848	# Cl
3.374	3634.	# K
3.721	7851.	# Ca
5.448	4538.	# Cr
5.970	673.	# Cr
6.436	17290.	# Fe
7.100	1946.	# Fe
7.507	1849.	# Ni

TABLE 2. TYPICAL PARTICLE DISTRIBUTION ON TEFLON ELECTRET

Total Feature Count is 540		Particle Size Distribution
Size	No.	Percentage (20 *'S=100%)
0	540	**********
5	518	**********
1	395	**********
1.5	258	*********
2	182	******
2.5	145	*****
3	84	***
3.5	55	**
4	40	*
4.5	24	
5	18	
5.5	11	
6	11	
6.5	9	
7	9	
7.5	9	
8	9	
8.5	2	
9	2	
9.5	1	
10	1	
50	0	

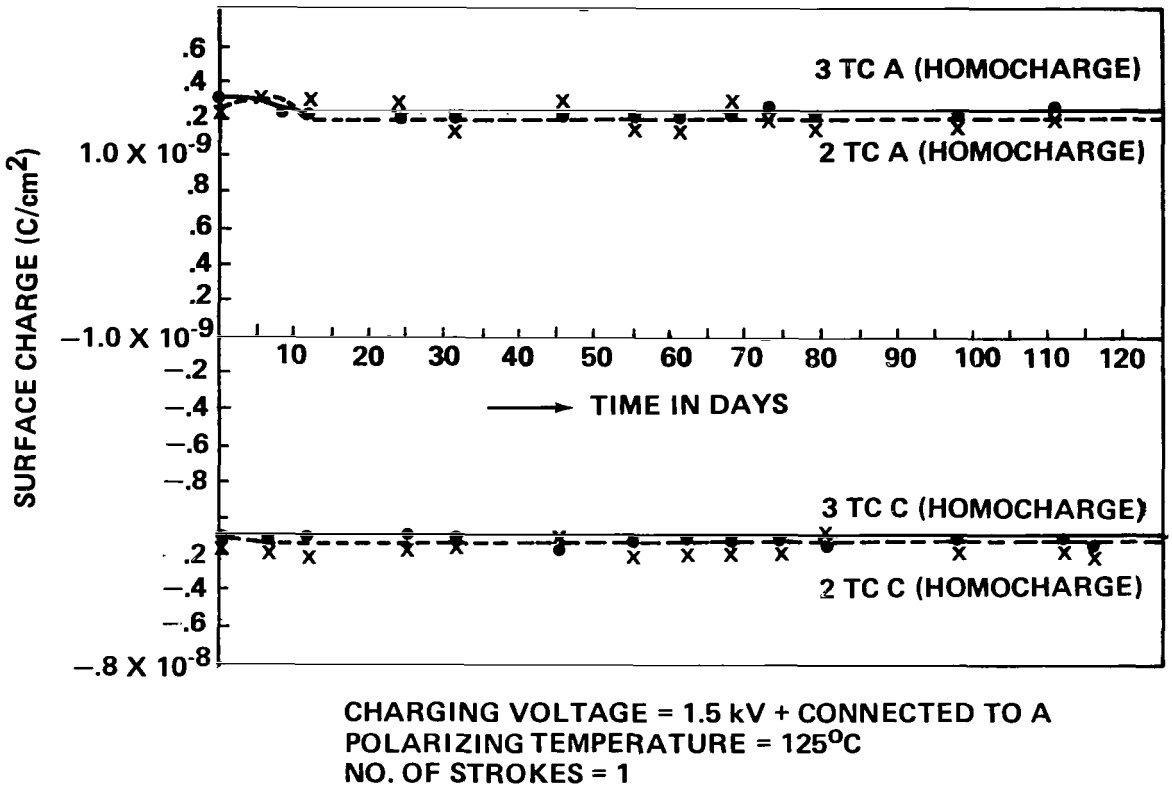
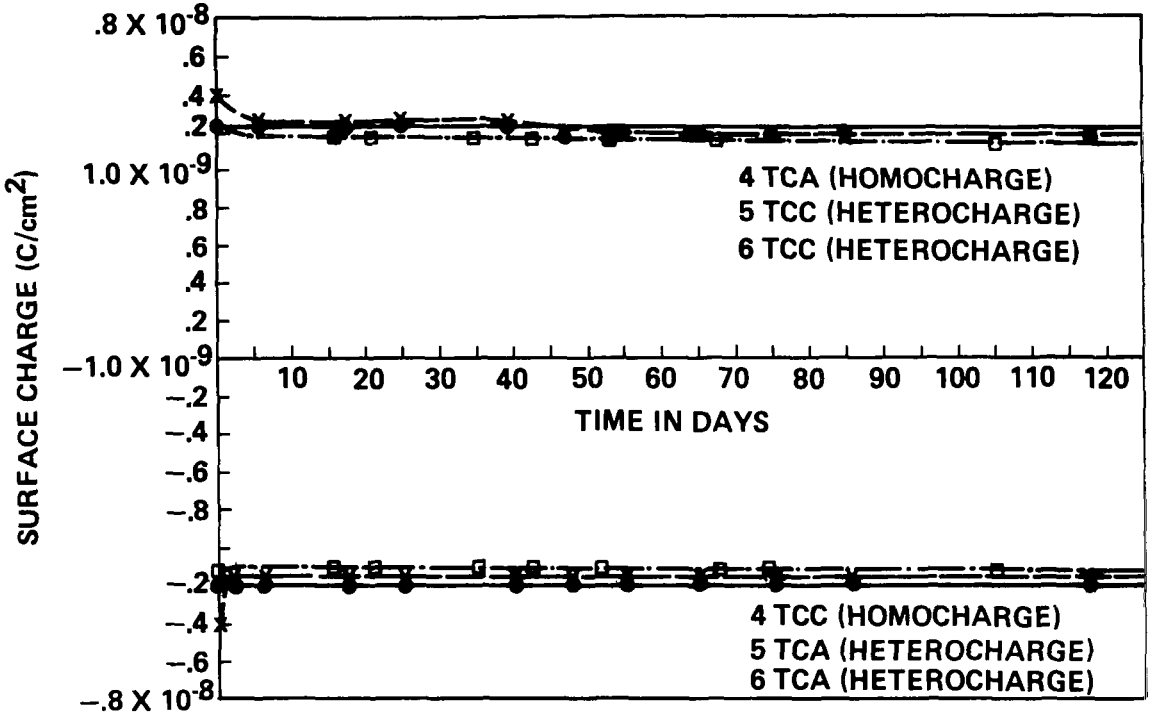


Figure 1. Charge decay characteristics of corona-charged Teflon electret. Two electret samples, no. 2 and 3. The letters A and C after the sample identification name refer to the side of the electret next to the anode and cathode, respectively.



CHARGING VOLTAGE = 7 kV FOR 5 TC, 8.5 kV FOR 6 TC, 1.5 kV FOR 4 TC AT T = 75°C
CHARGING TEMPERATURE = 120°C FOR 5 TC AND 6 TC
THICKNESS OF SAMPLE = 0.165 mm
NO. OF STROKES = 1

Figure 2. Charge decay characteristics of corona-charged Teflon electrets. These curves show that for sample 4TC formed at 75°C the charge is homo, while samples 5TC and 6TC are heterocharged.

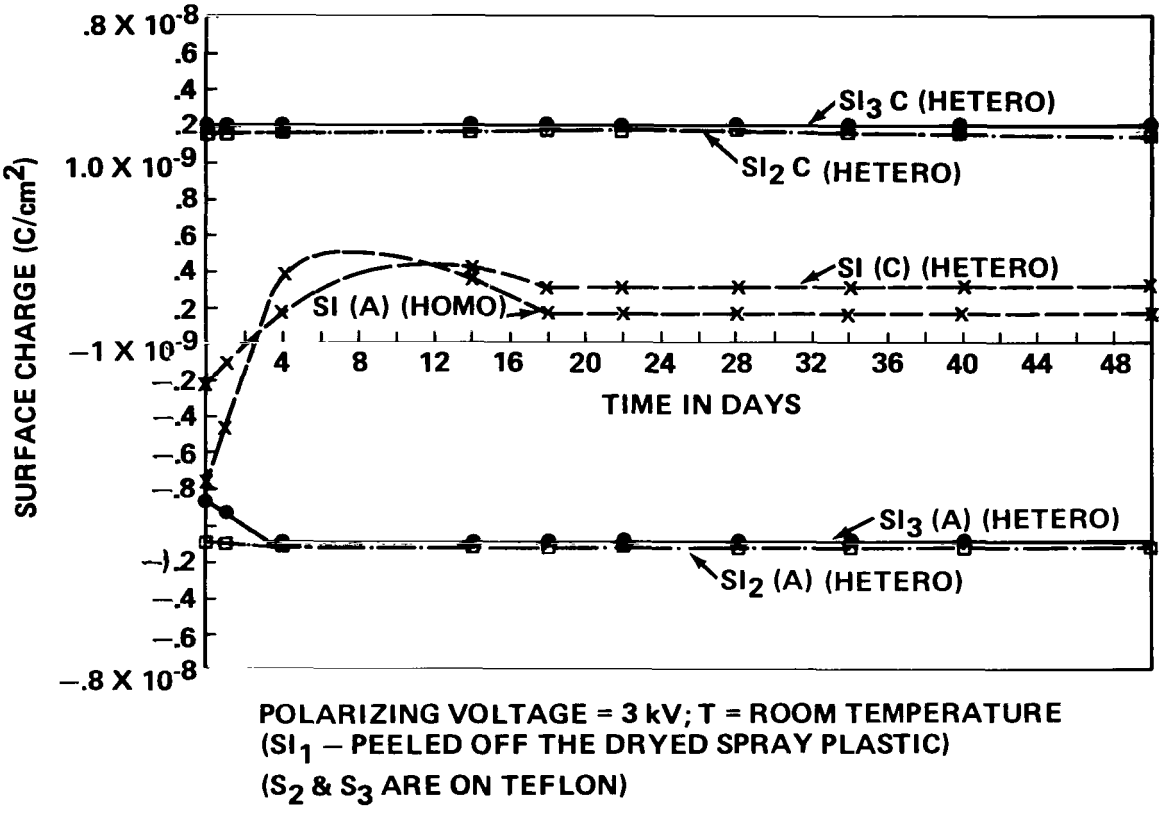


Figure 3. Charge decay characteristics of electrets prepared by plastic spray (3M brand "77" adhesive) through a brush corona (charge injection spray gun). SI_1, SI_2, and SI_3 refer to sprayed deposition samples 1, 2, and 3. A and C refer to the anode and cathode electrodes.

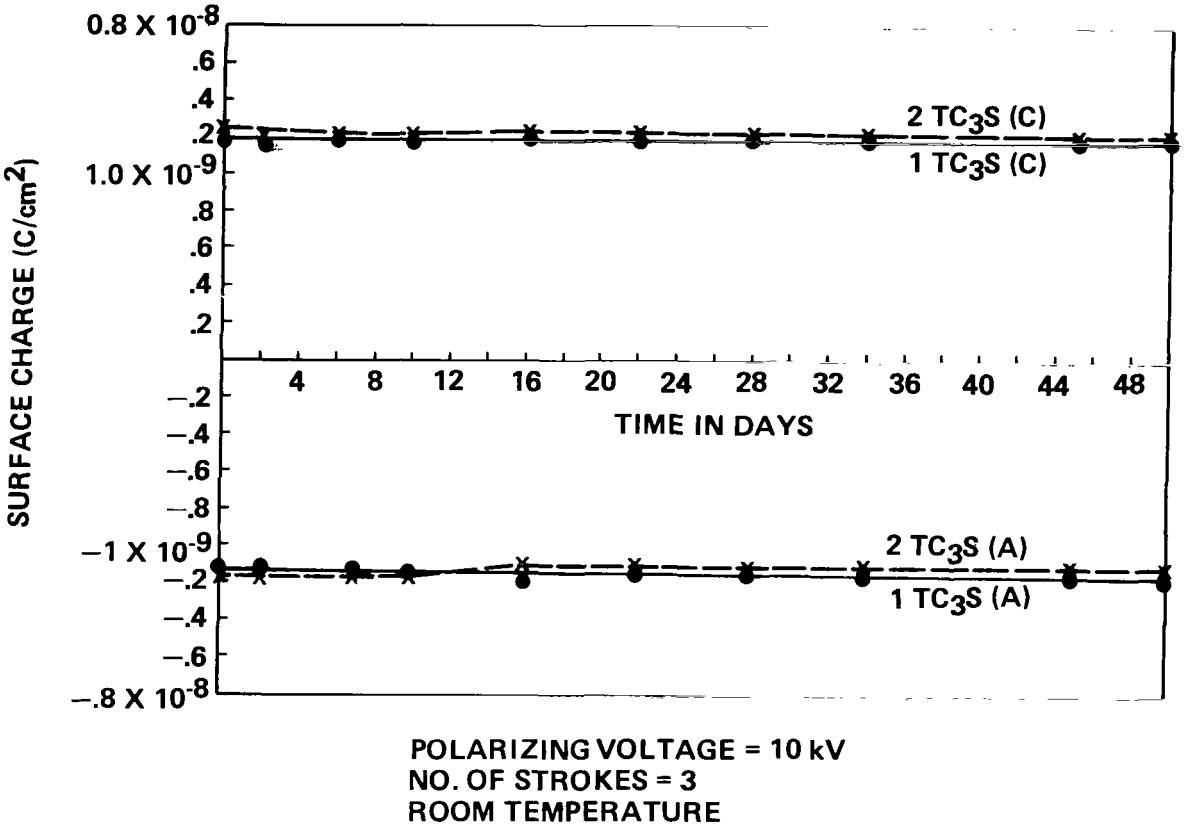


Figure 4. Surface charge decay characteristics of corona-charged Teflon electrets. Samples 1T and 2T were prepared under the same conditions.

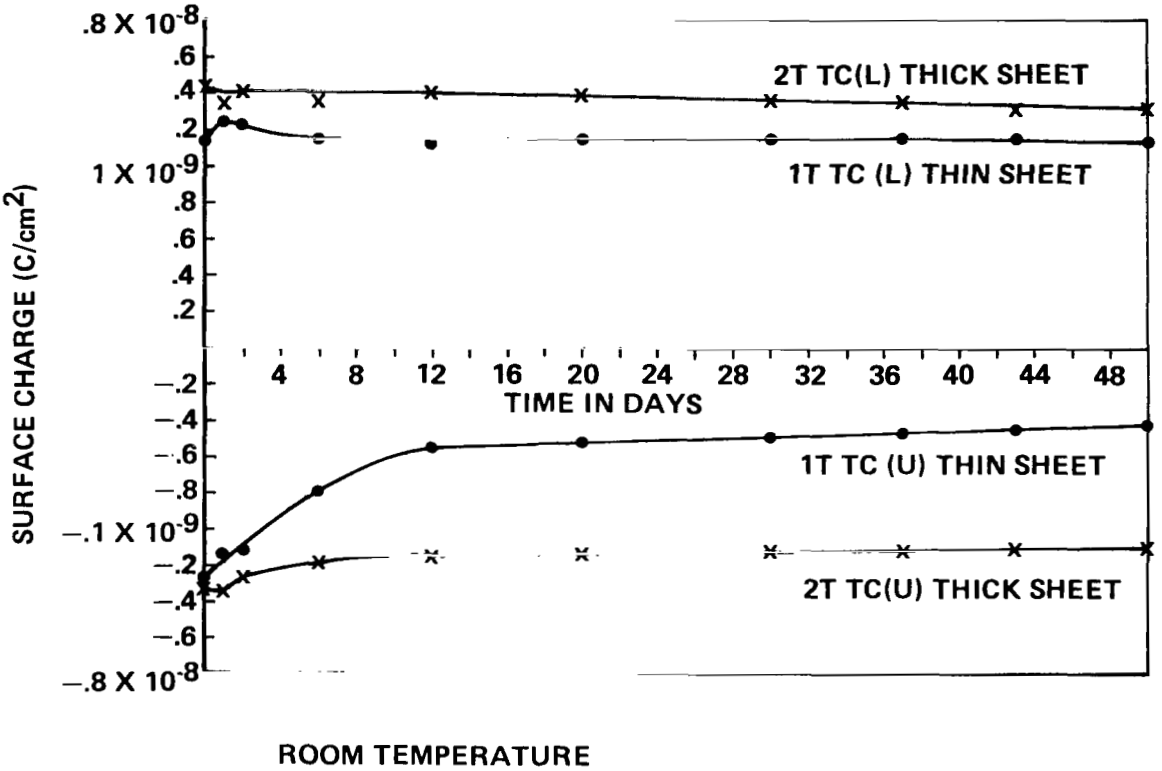


Figure 5. Charge decay characteristics of electret prepared by charging with Tesla coil. 1T and 2T refer to sample number. (U) and (L) refer to upper and lower surfaces of the samples.

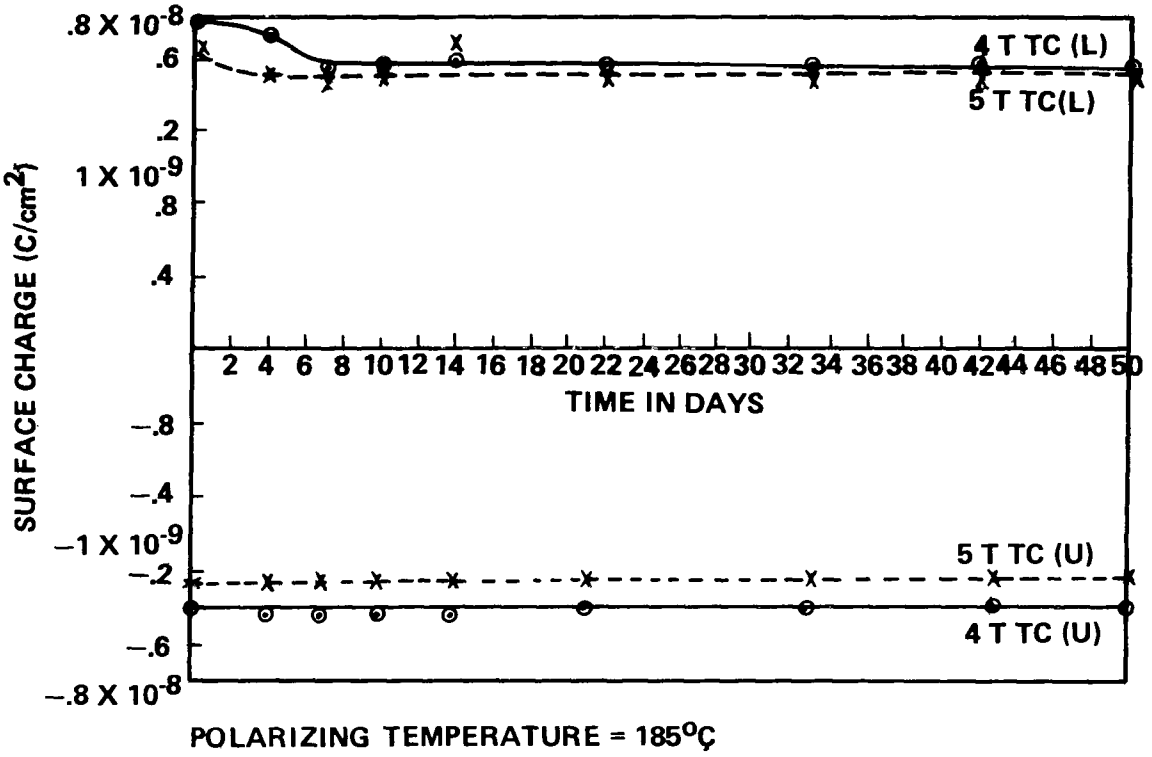


Figure 6. Charge decay characteristics of Tesla-coil charged Teflon electrets. The nomenclature is the same as Figure 5.

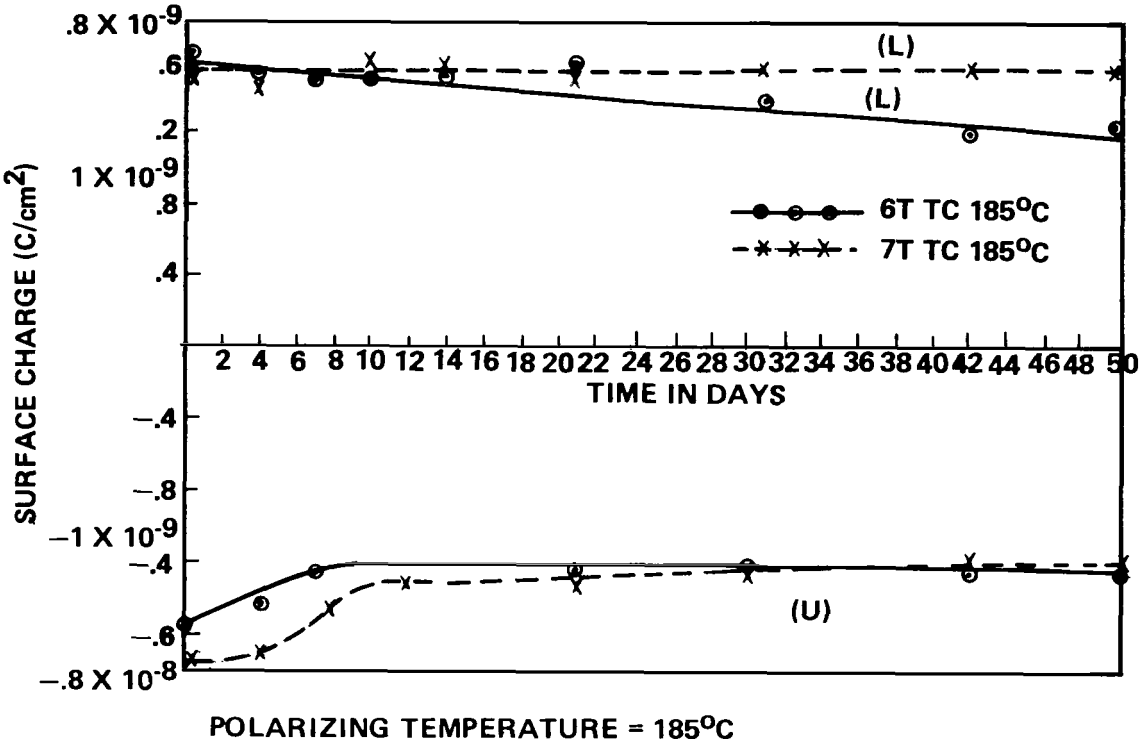


Figure 7. Charge decay characteristics of Teflon electrets charged with Tesla coil. Nomenclature is the same as Figure 5.

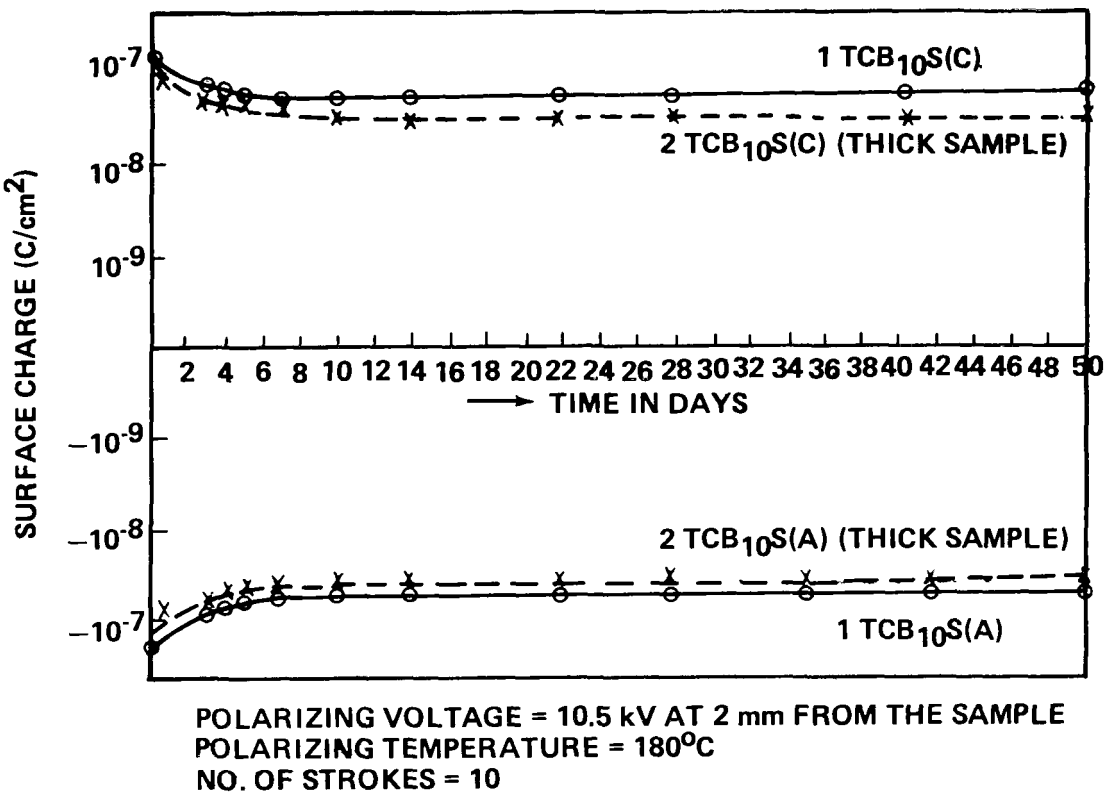


Figure 8. Charge decay characteristics of brush-corona charged Teflon electrets. Nomenclature of samples same as Figure 1 except that CB_{10} refers to corona brush with 10 strokes.

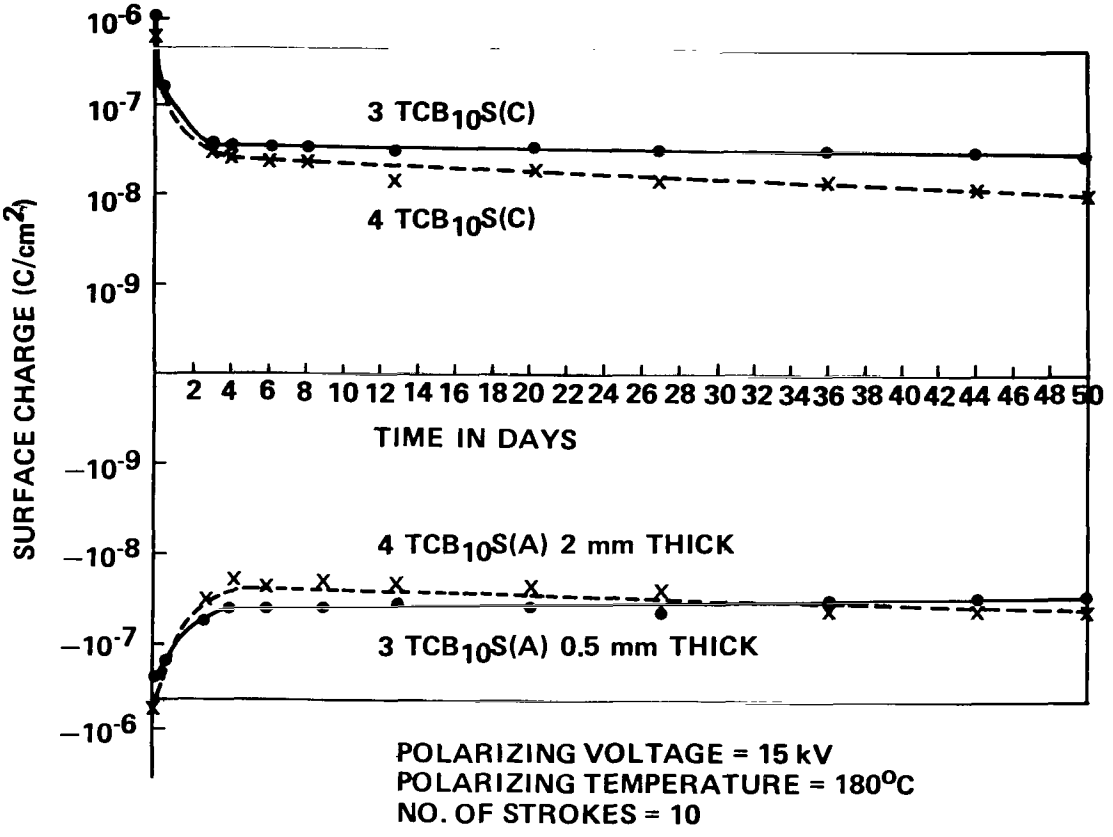


Figure 9. Charge decay characteristics of brush-corona charged Teflon electrets. Nomenclature of samples same as Figure 8.

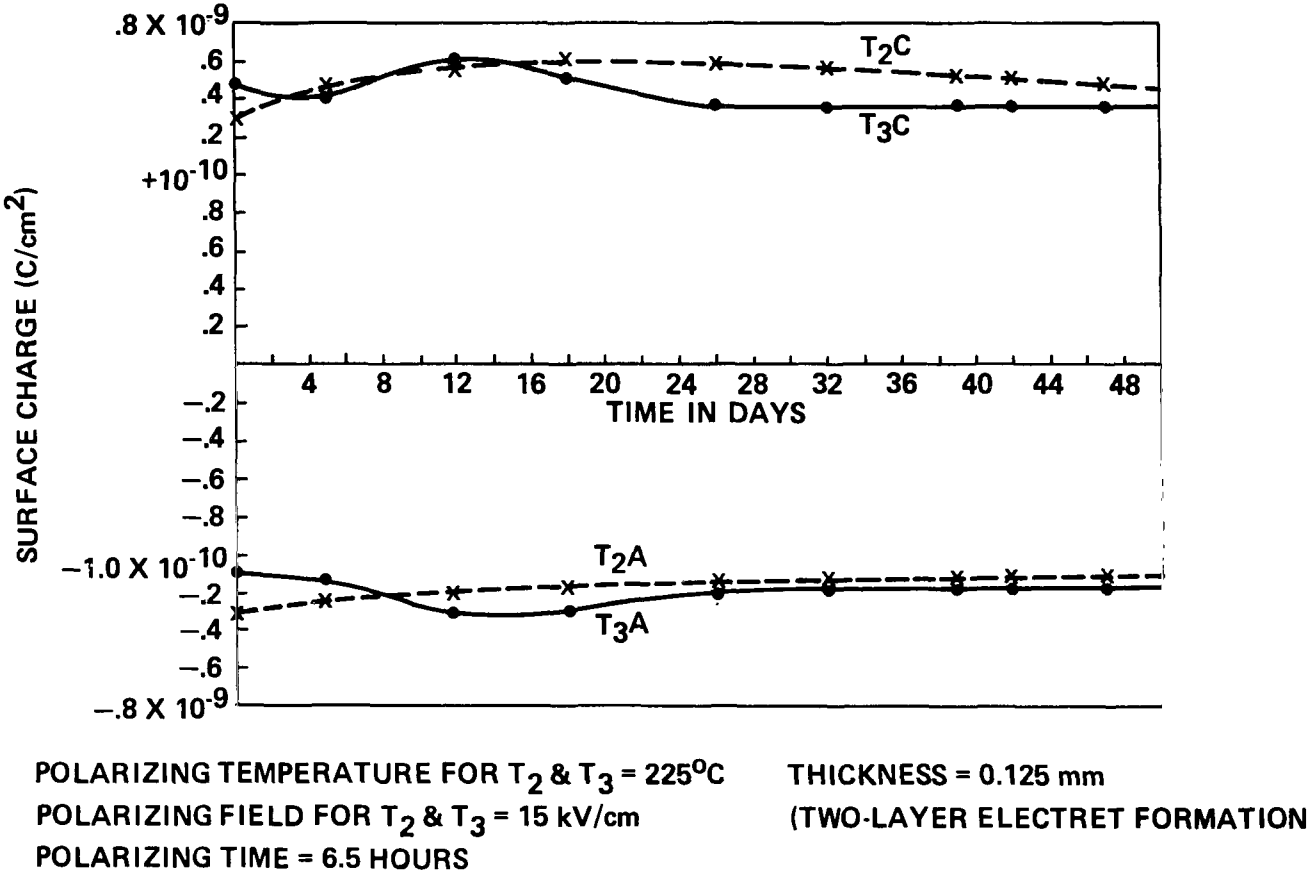


Figure 10. Charge decay characteristics of volume-polarized Teflon thermoelectrets. T_2 and T_3 refer to different layers of a 2-layer set of Teflon dielectric sheets between two electrodes.

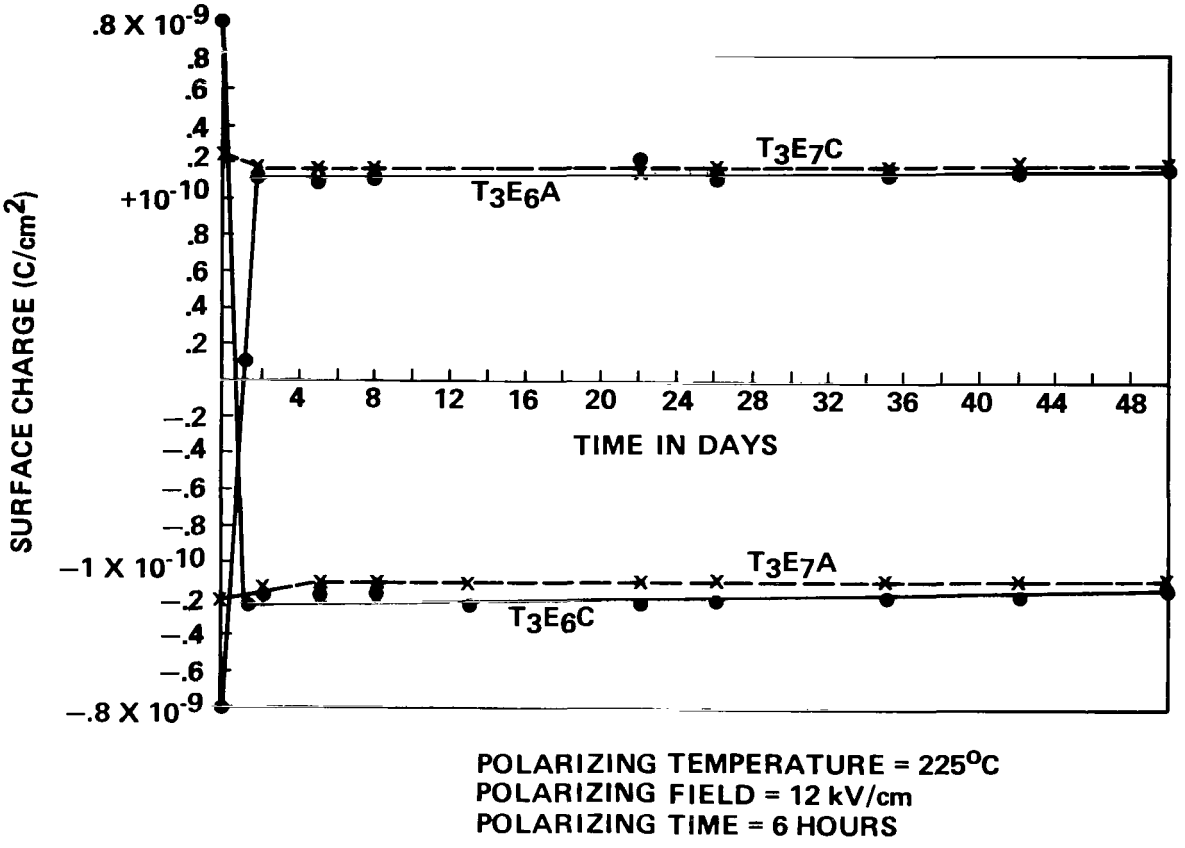


Figure 11. Charge decay characteristics of Teflon electrets. T_3 refers to the third layer of three dielectric sheets. E_6 and E_7 are samples 6 and 7 from this sheet.

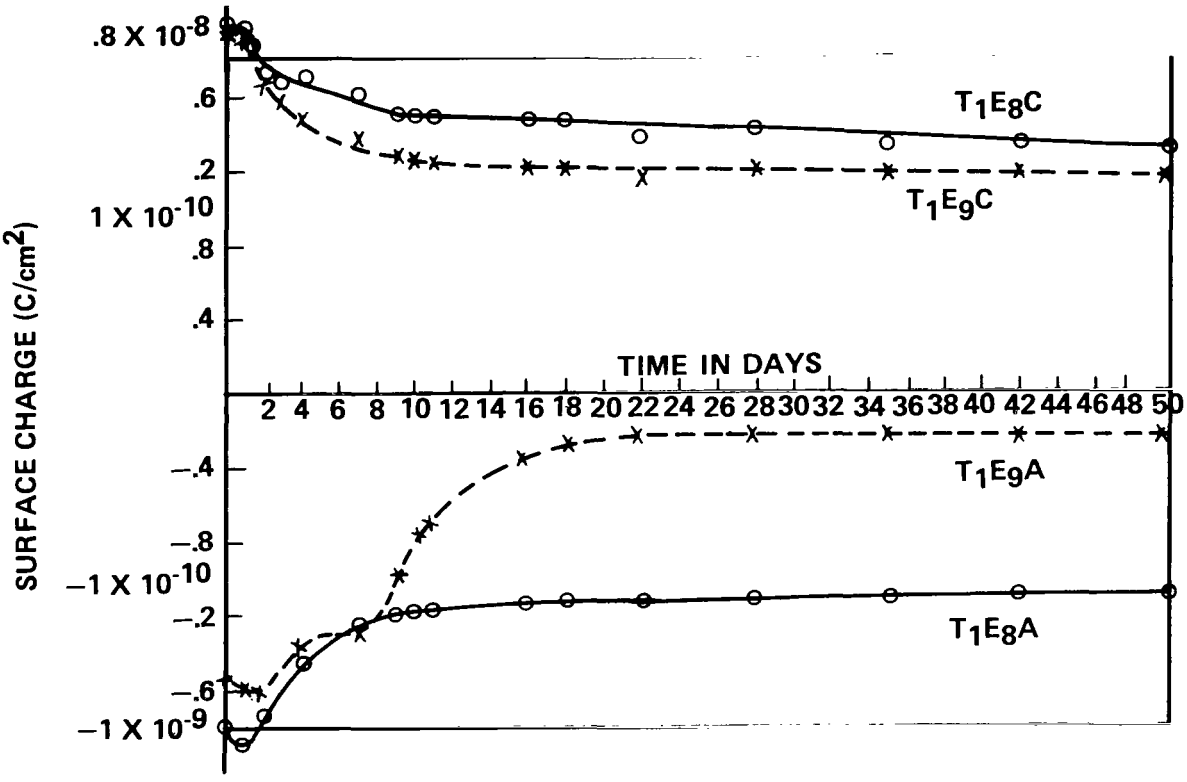


Figure 12. Charge decay characteristics of Teflon electrets. Nomenclature of samples is the same as Figure 11.

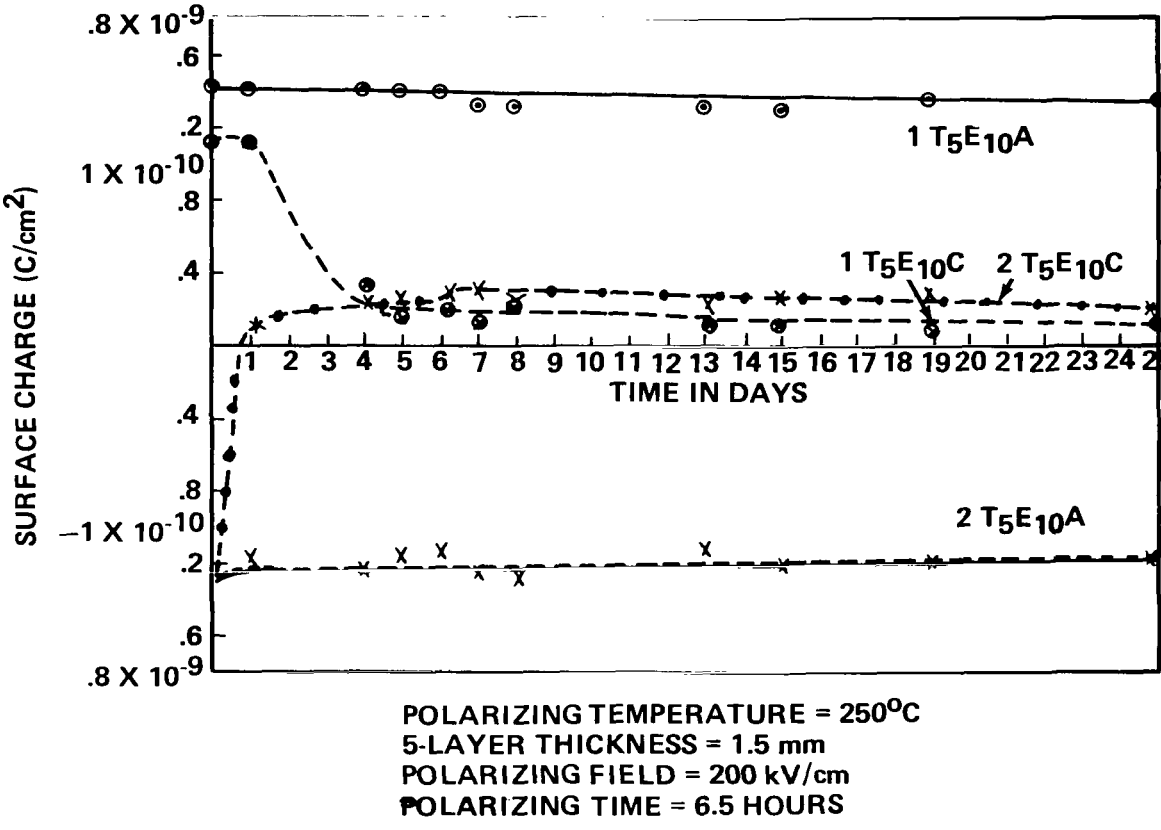


Figure 13. Charge decay characteristics of 5-layer thermoelectrets (layers 1 and 2). 1 and 2 refer to layers 1 and 2; E_{10} refers to electret sample number.

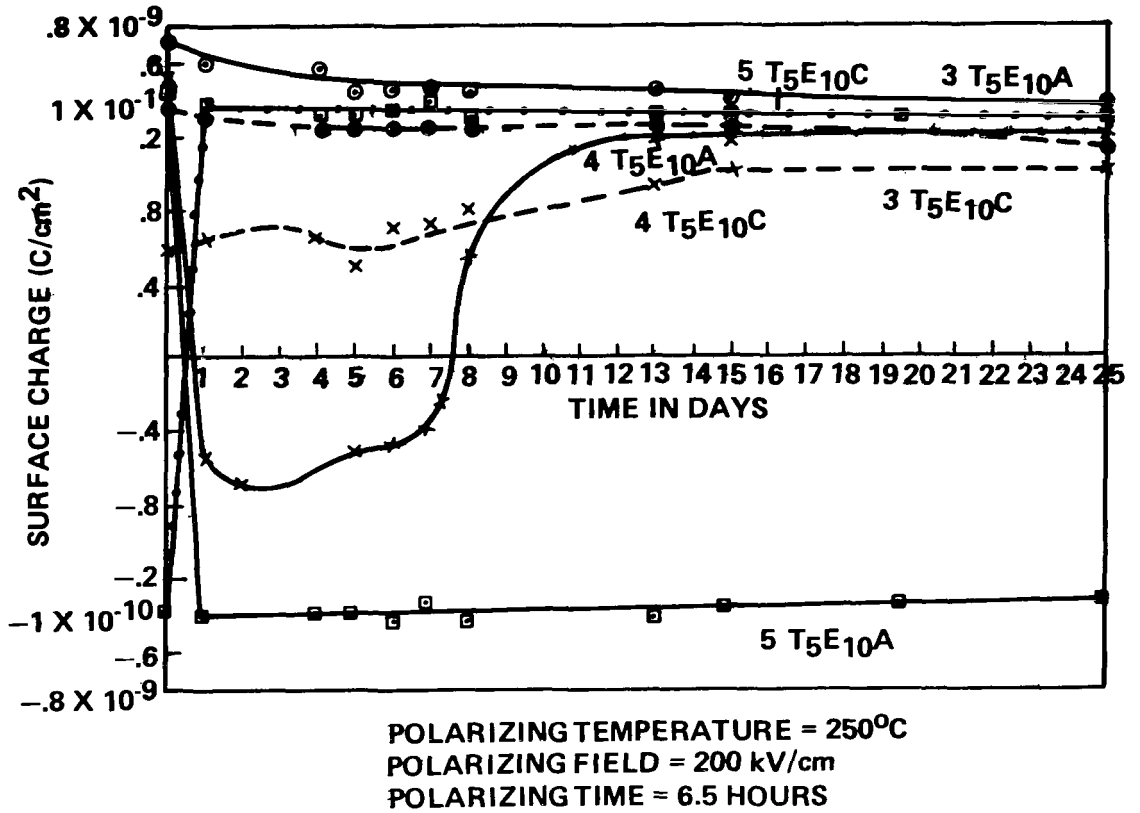


Figure 14. Charge decay characteristics of 5-layer thermoelectrets. Nomenclature is same as Figure 13.

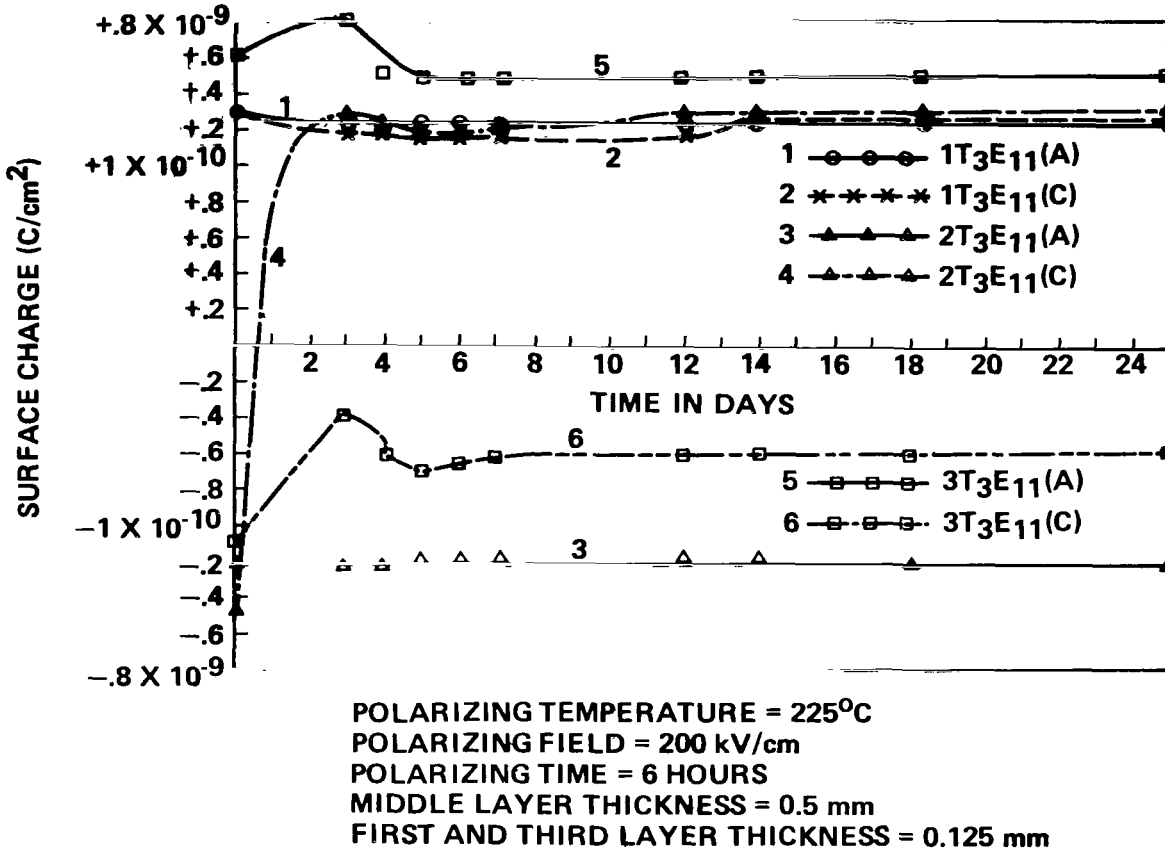
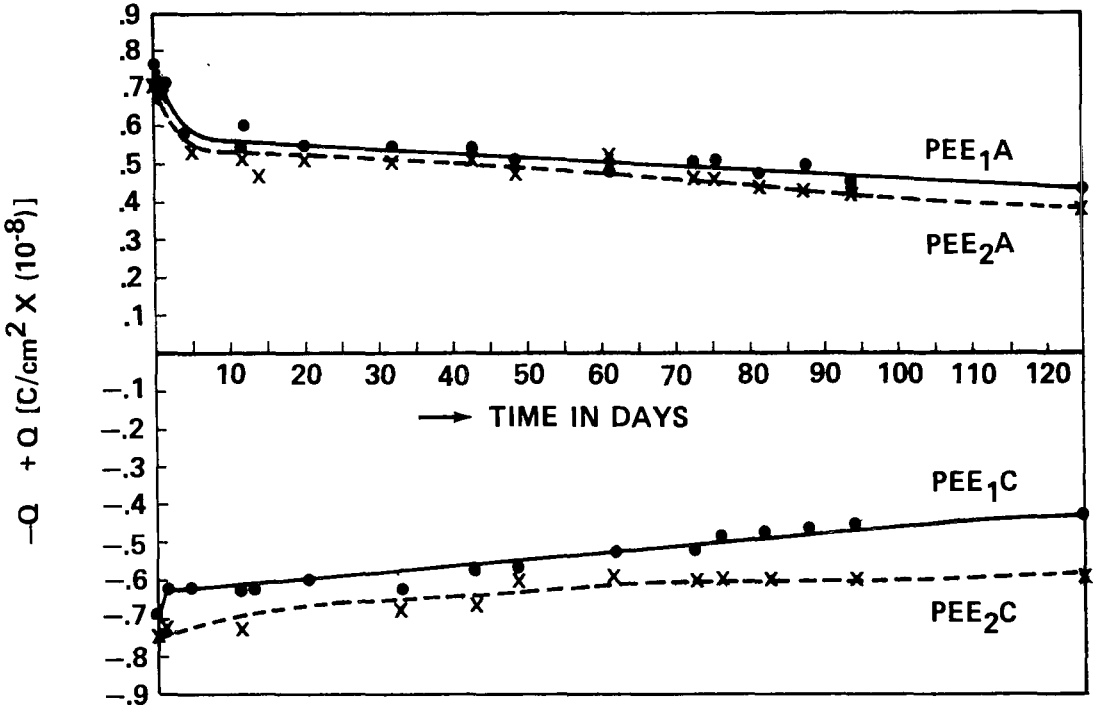


Figure 15. Charge decay characteristics of 3-layer Teflon electrets. Nomenclature is same as Figure 13.



FOR PEE_1A, POLARIZING TEMPERATURE = 70°C AND POLARIZING VOLTAGE = 5.5 kV
AT 5 mm FROM SAMPLE (POSITIVE CORONA ON UPPER SURFACE LOWER SURFACE GROUNDED)
FOR PEE_2A, POLARIZING TEMPERATURE = 70°C AND POLARIZING VOLTAGE = 5.5 kV
AT 5 mm FROM SAMPLE

Figure 16. Charge decay characteristics of brush-corona charged polyethylene thermoelectrets. Nomenclature is PE for polyethylene; 1 and 2 refer to different electrets.

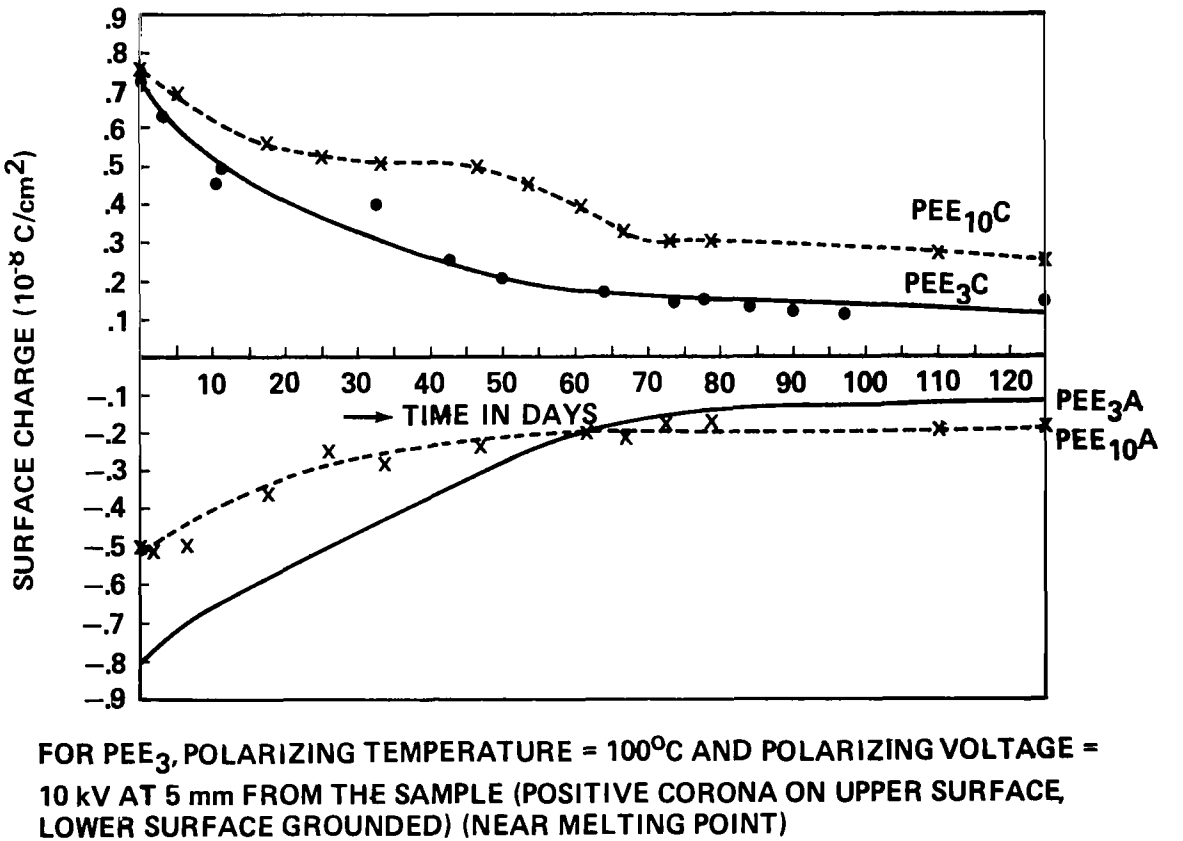
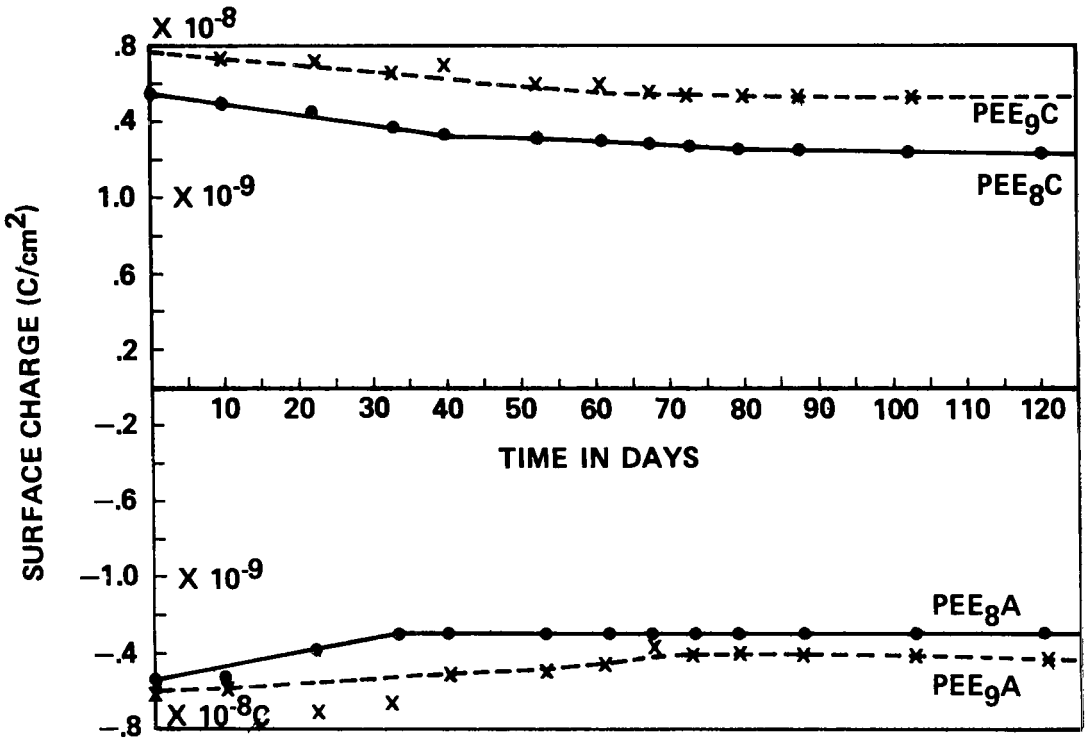
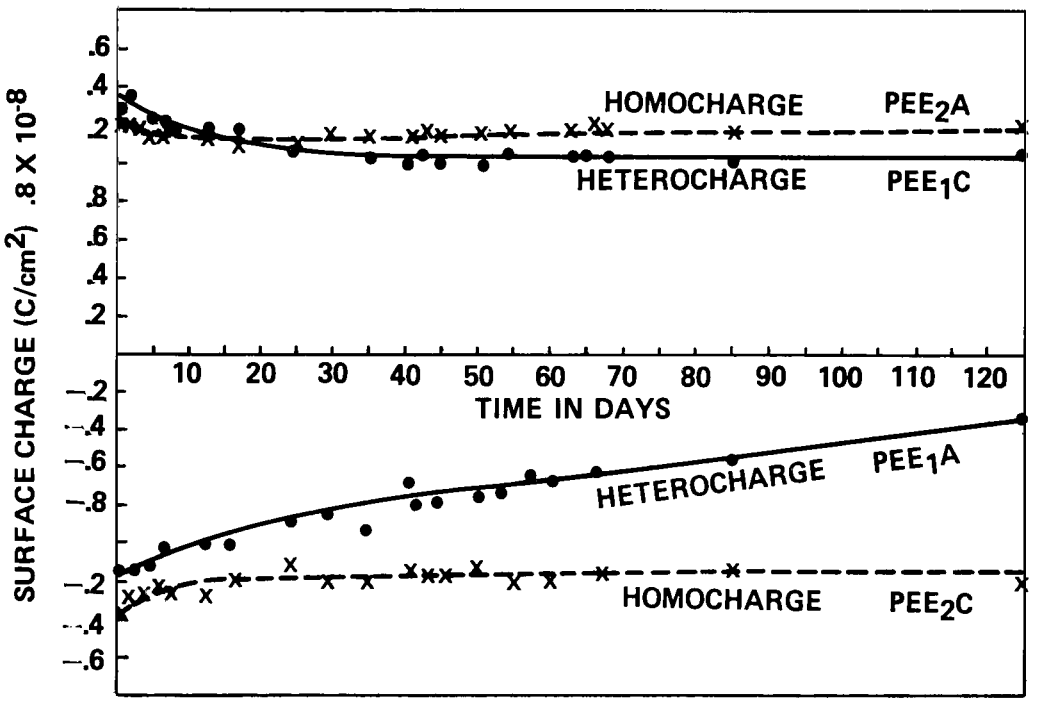


Figure 17. Charge decay characteristics of brush-corona charged polyethylene thermoelectrets. Nomenclature is same as Figure 16. A refers to upper surface and C to lower surface.



FOR PEE_8, POLARIZING TEMPERATURE = 100°C AND POLARIZING VOLTAGE = 10 kV AT 5 mm FROM SAMPLE.
FOR PEE_{10}, POLARIZING TEMPERATURE = 90°C AND POLARIZING VOLTAGE = 10 kV AT 5 mm FROM SAMPLE.

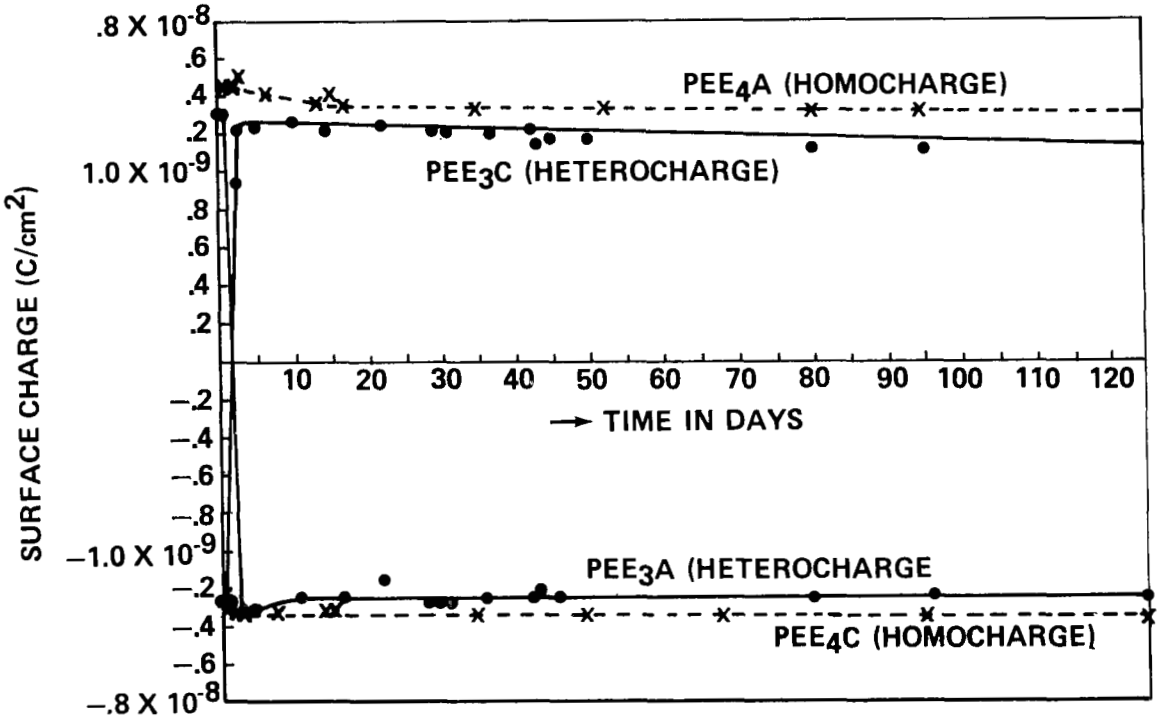
Figure 18. Charge decay characteristics of brush-corona charged polyethylene thermoelectrets. Nomenclature is same as Figure 17.



FOR PEE_1, POLARIZING TEMPERATURE = 100°C; POLARIZING TIME = 7 HOURS; POLARIZING FIELD = 90 kV/cm; THICKNESS = 0.32 cm

FOR PEE_2, POLARIZING TEMPERATURE = 100°C; POLARIZING TIME = 8 HOURS; POLARIZING FIELD = 62.5 kV/cm; THICKNESS = 0.32 cm

Figure 19. Charge decay characteristics of the polyethylene thermoelectrets. Nomenclature is same as Figure 17.



FOR PEE_3, POLARIZING TEMPERATURE = 100°C; POLARIZING TIME = 8 HOURS; POLARIZING FIELD = 22 kV/cm
FOR PEE_4, POLARIZING TEMPERATURE = 100°C; POLARIZING TIME = 8 HOURS; POLARIZING FIELD = 15.6 kV/cm
THICKNESS = 0.32 cm

Figure 20. Charge decay characteristics of polyethylene thermoelectrets. Nomenclature is same as Figure 17.

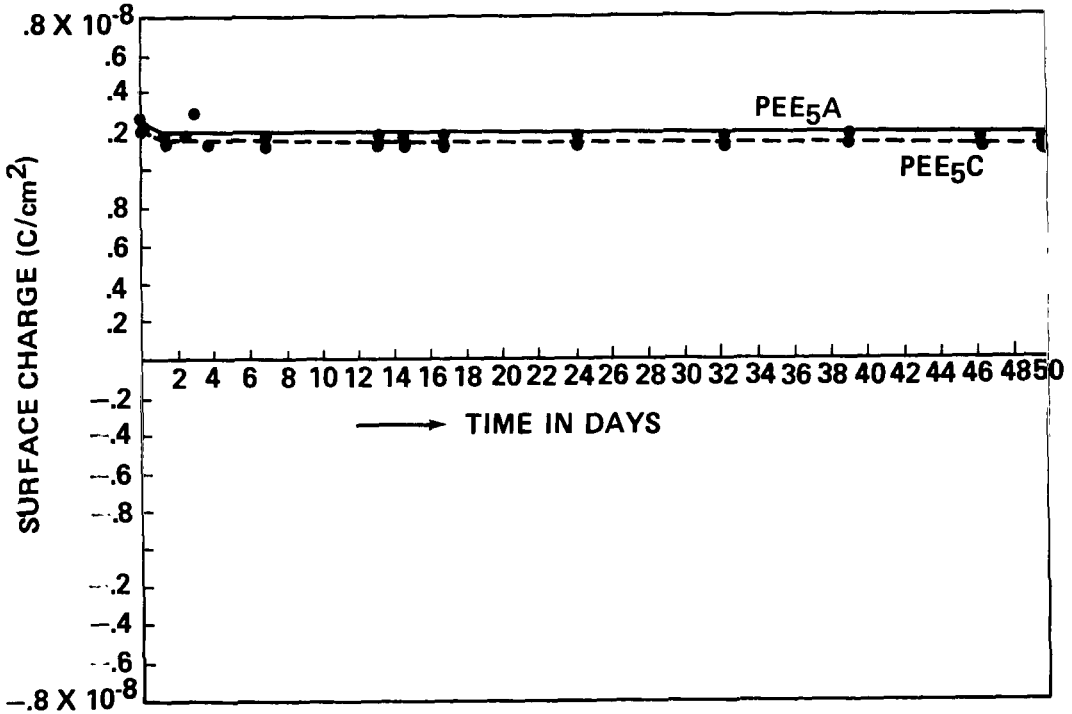


Figure 21. Charge decay characteristics of polyethylene thermoelectrets. Nomenclature is same as Figure 17.

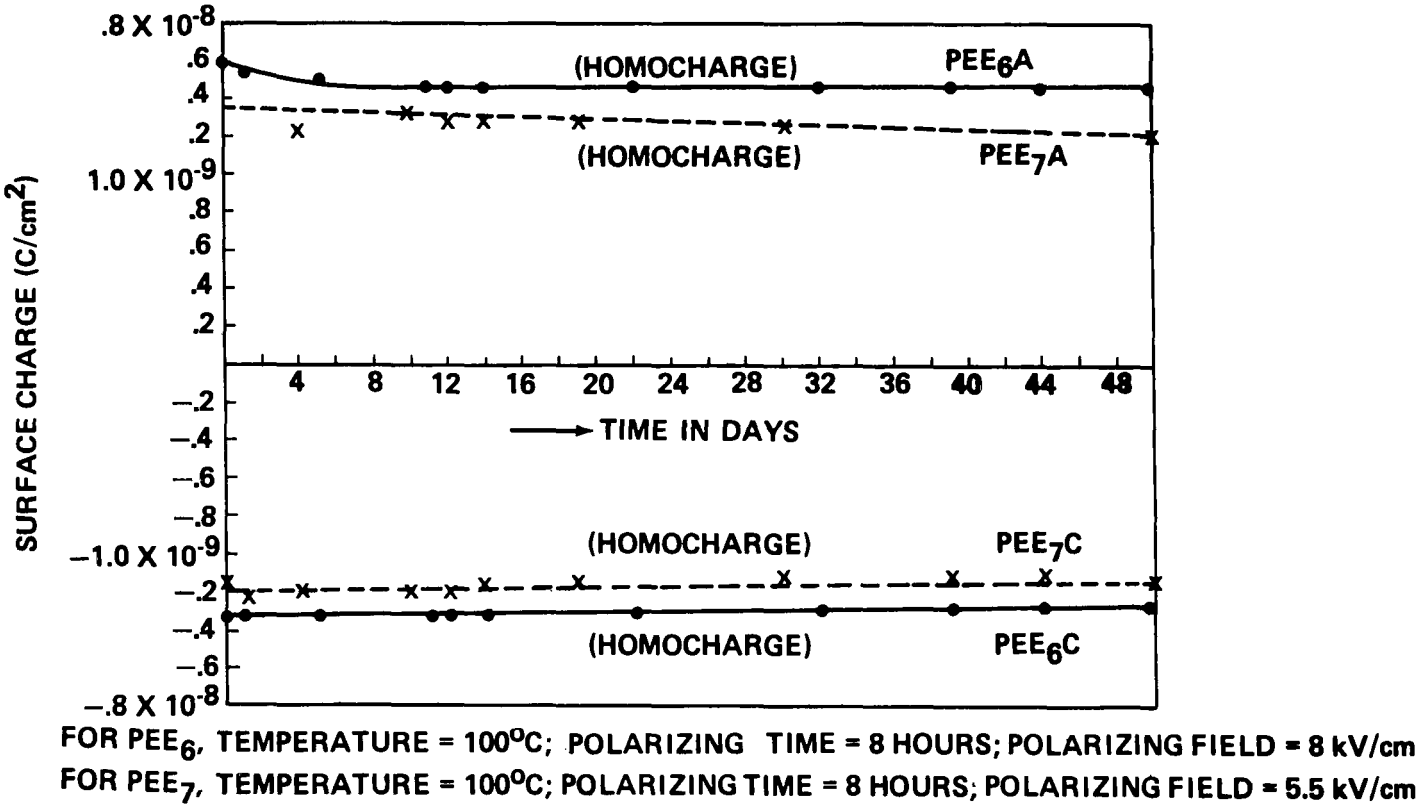


Figure 22. Charge decay characteristics of polyethylene thermoelectrets. Nomenclature is same as Figure 17.

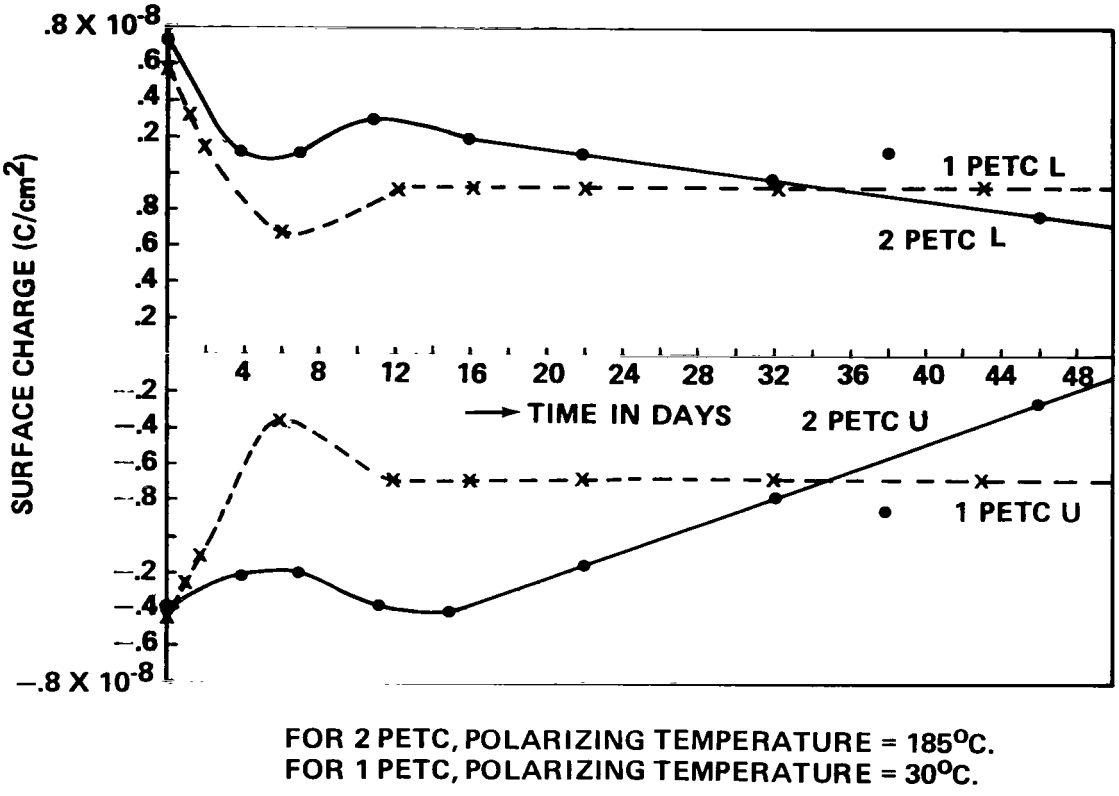
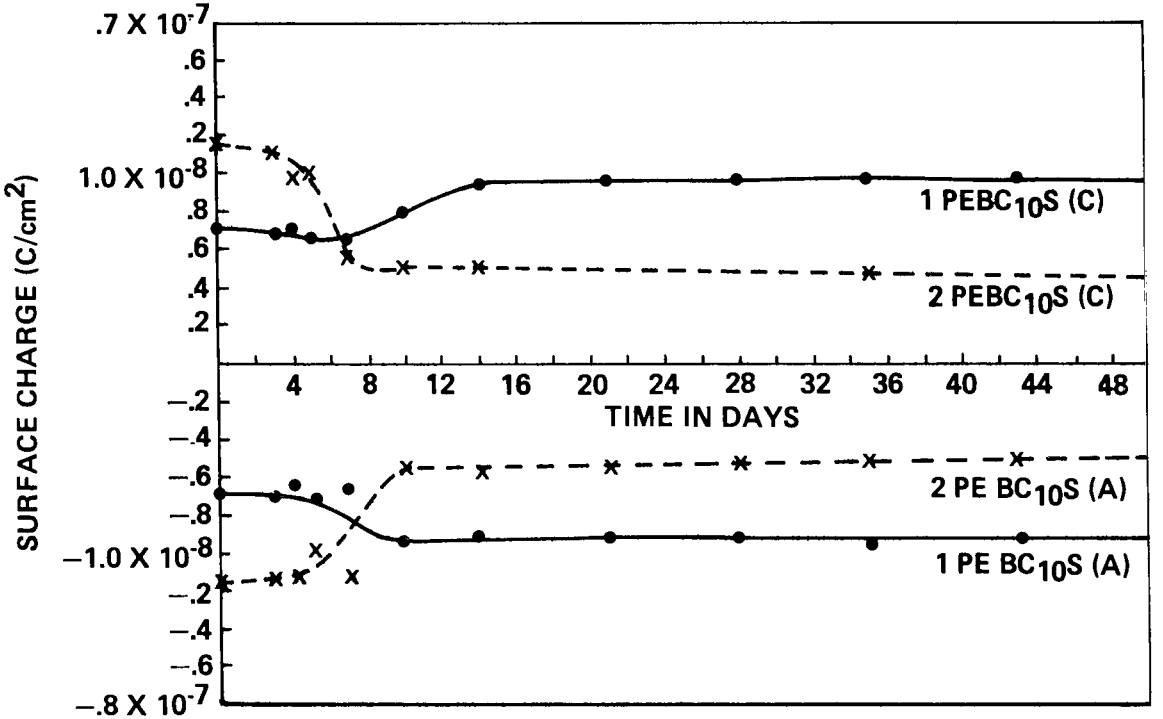
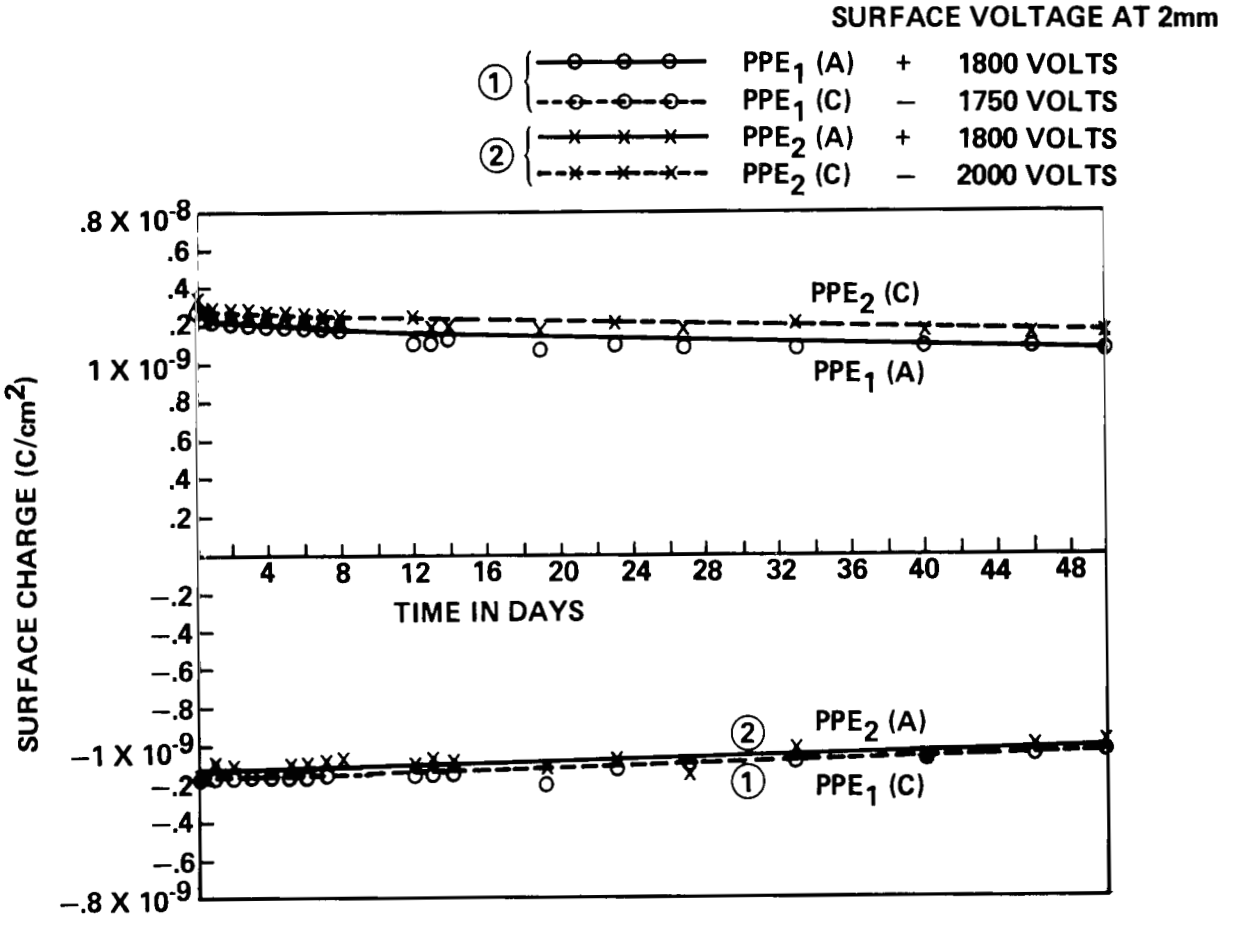


Figure 23. Charge decay characteristics of polyethylene electrets charged with Tesla coil for a few seconds. PE referes to polyethylene. 1 and 2 refer to different electrets. TC refers to Tesla coil, and U and L refer to upper and lower surfaces, respectively.



FOR 1 PEBC$_{10}$S, POLARIZING TEMPERATURE = 100°C; POLARIZING FIELD = 14.5 kV; NO. OF STROKES = 10
FOR 2 PEBC$_{10}$S; POLARIZING TEMPERATURE = 100°C; POLARIZING FIELD = 14.5 kV; NO. OF STROKES = 10

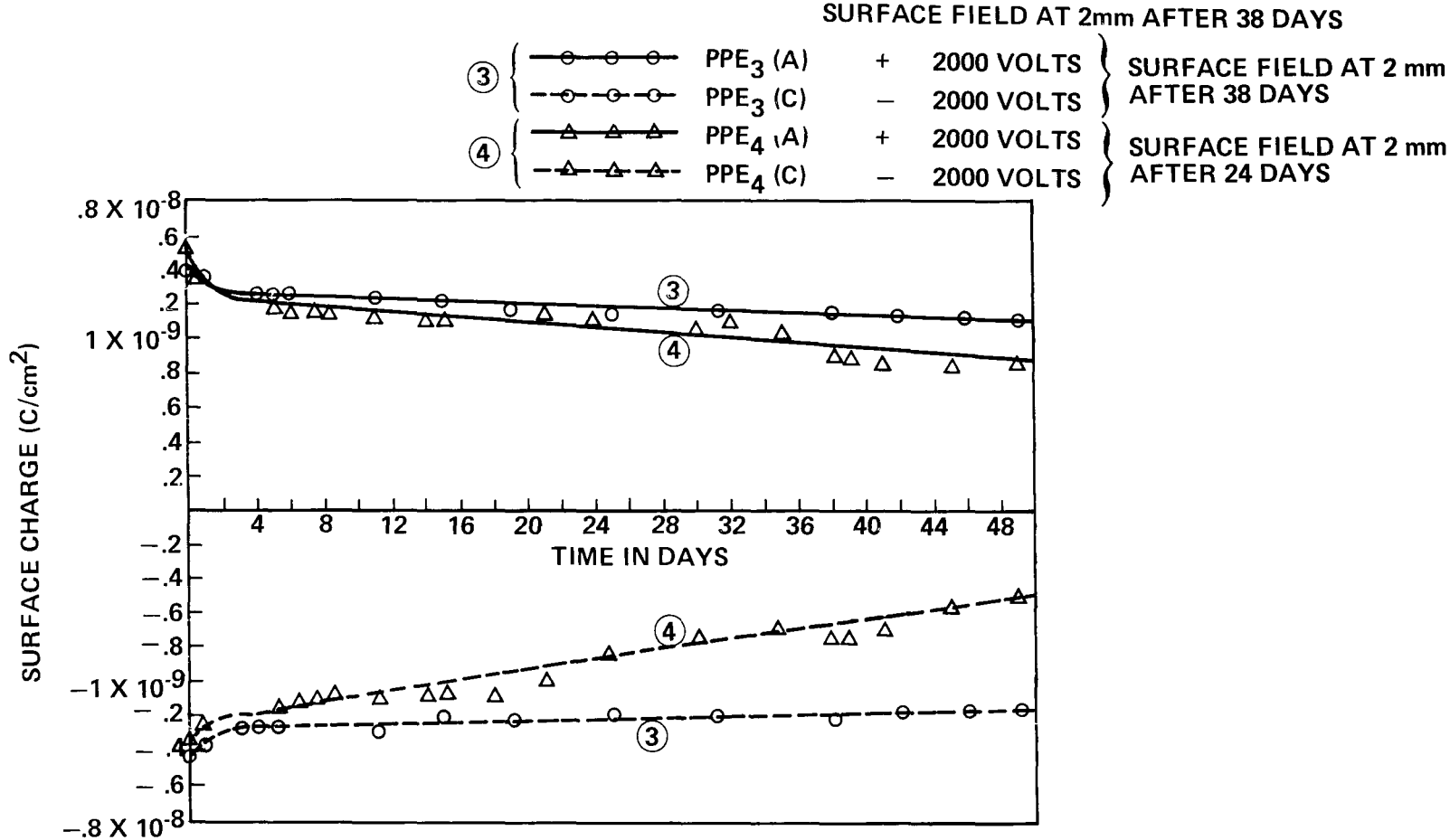
Figure 24. Charge decay characteristics of polyethylene electrets charged with 10-stroke brush corona charge. 1 and 2 refer to sample number. PE refers to polyethylene. $BC_{10}S$ refers to 10-stroke brush corona charging.



FOR PPE_1, POLARIZING VOLTAGE = 17.5 kV/cm^2; POLARIZING TIME = 7 HOURS, THICKNESS = 0.315 mm; TEMPERATURE = 170°C.

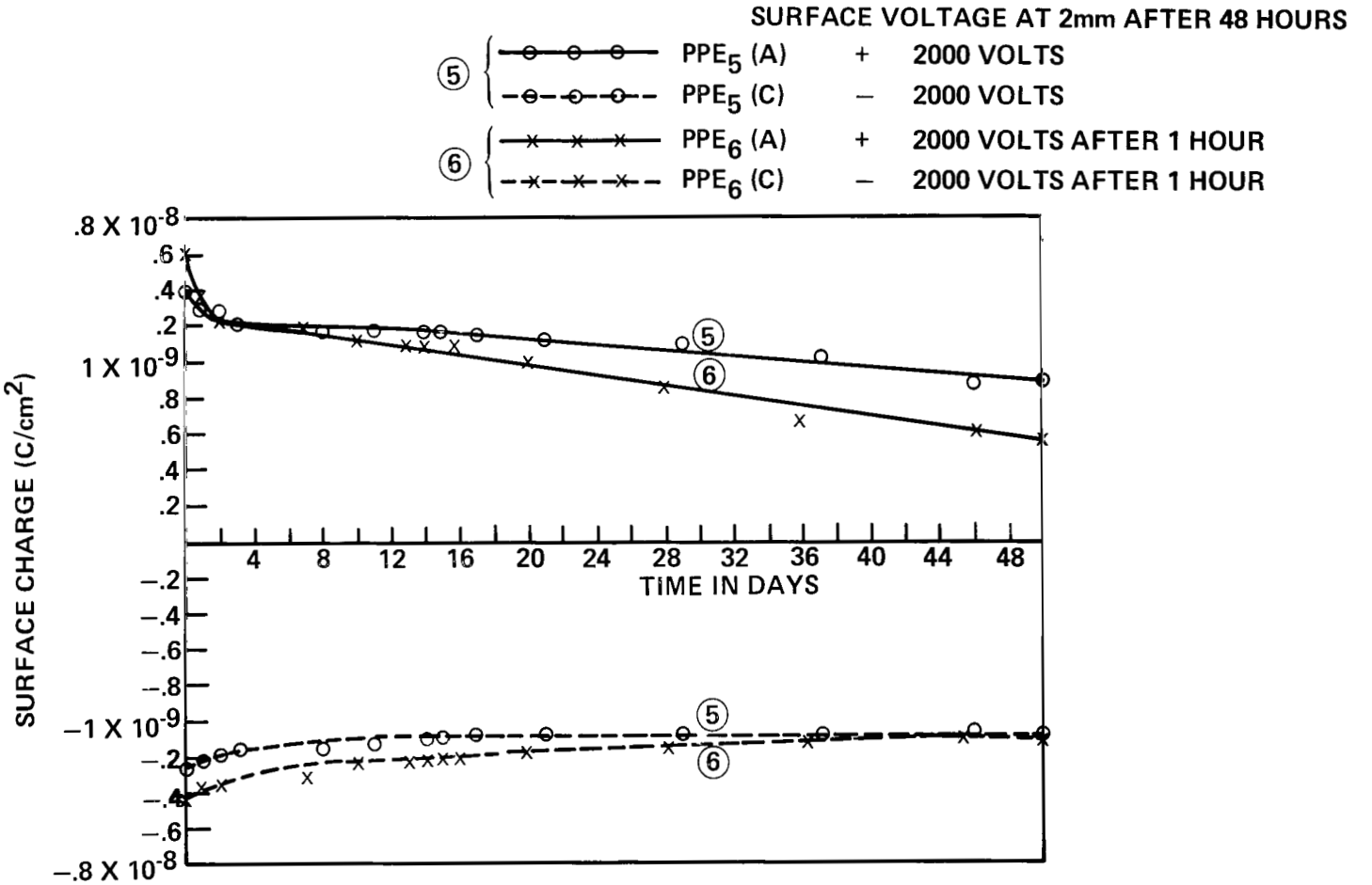
FOR PPE_2, POLARIZING VOLTAGE = 14 kV/cm^2; POLARIZING TIME = 8 HOURS; THICKNESS = 0.315 mm; TEMPERATURE = 170°C

Figure 25. Charge decay characteristics of polypropylene thermoelectrets. PP refers to polypropylene. E_1 and E_2 refer to electret sample number.



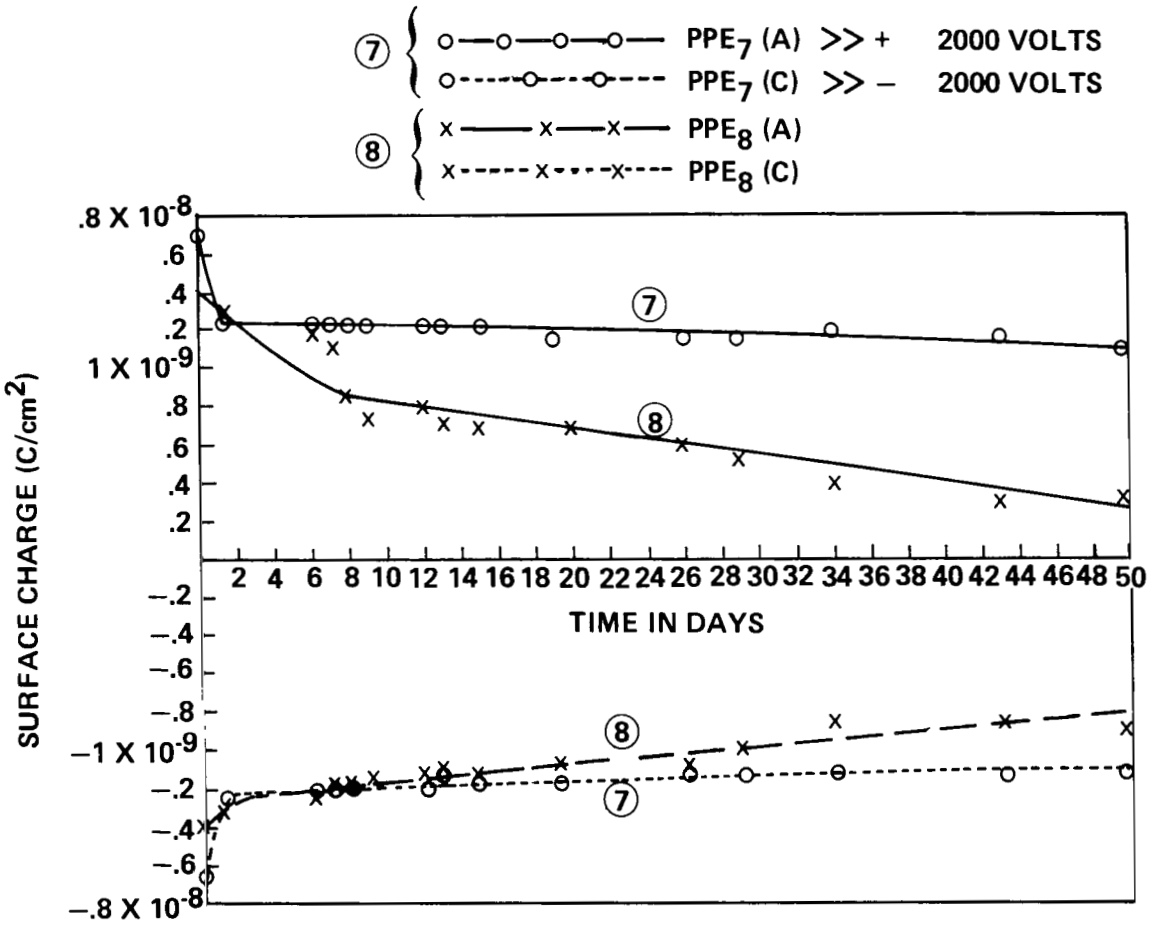
FOR PPE_3, POLARIZING VOLTAGE = 13.7 kV/cm; POLARIZING TIME = 8 HOURS; POLARIZING TEMPERATURE = 160°C; THICKNESS = 0.315 mm.
FOR PPE_4, POLARIZING VOLTAGE = 7.7 kV/cm; POLARIZING TIME = 8 HOURS; POLARIZING TEMPERATURE = 160°C; THICKNESS = 0.315 mm.
(SAMPLE BETWEEN MICA ELECTRODES)

Figure 26. Surface charge decay characteristics of polypropylene thermoelectrets. Nomenclature same as Figure 24.



FOR PPE_5, POLARIZING VOLTAGE = 16 kV/cm^2; POLARIZING TIME = 8 HOURS; POLARIZING TEMPERATURE = 160°C; THICKNESS = 0.315 mm.
FOR PPE_6, POLARIZING VOLTAGE = 44 kV/cm^2; POLARIZING TIME = 8 HOURS; POLARIZING TEMPERATURE = 160°C; THICKNESS = 0.315 mm.
(SHIELD WITH MICA ELECTRODE ON EITHER SIDE).

Figure 27. Surface charge decay characteristics of polypropylene thermoelectrets. Nomenclature same as Figure 24.



FOR PPE_7, POLARIZING VOLTAGE = 8 kV/cm^2; POLARIZING TIME = 8 HOURS; POLARIZING TEMPERATURE = 160°C; THICKNESS = 0.315 mm.
FOR PPE_8, POLARIZING VOLTAGE = 5 kV/cm^2; POLARIZING TIME = 8 HOURS; POLARIZING TEMPERATURE = 160°C; THICKNESS = 0.315 mm.

Figure 28. Surface charge decay characteristics of polypropylene thermoelectrets. Nomenclature same as Figure 24.

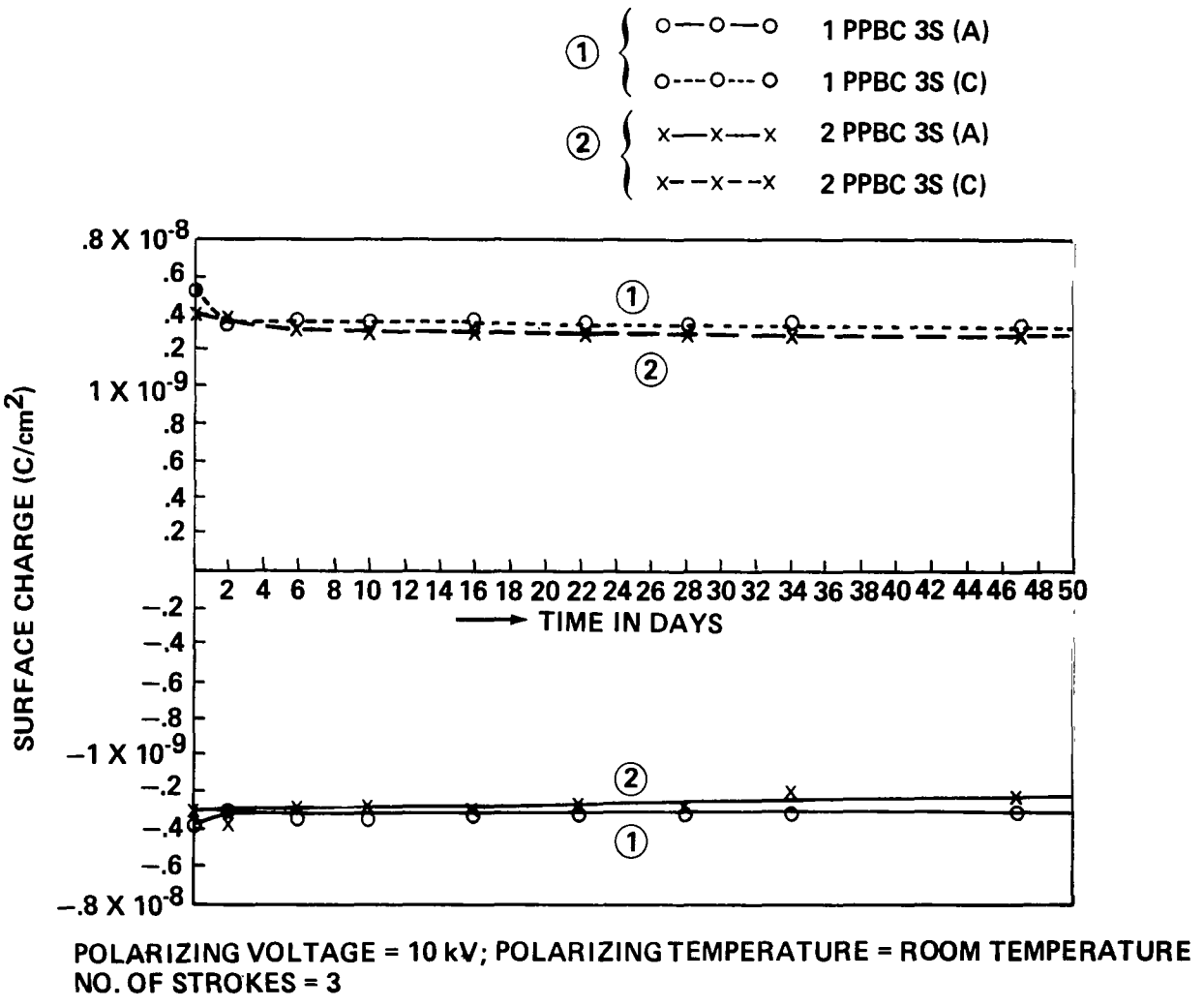


Figure 29. Surface charge decay characteristics of brush-corona charged polypropylene electrets. 1 and 2 refer to sample number. PP refers to polypropylene. BC3S refers to brush corona charge, 3 strokes.

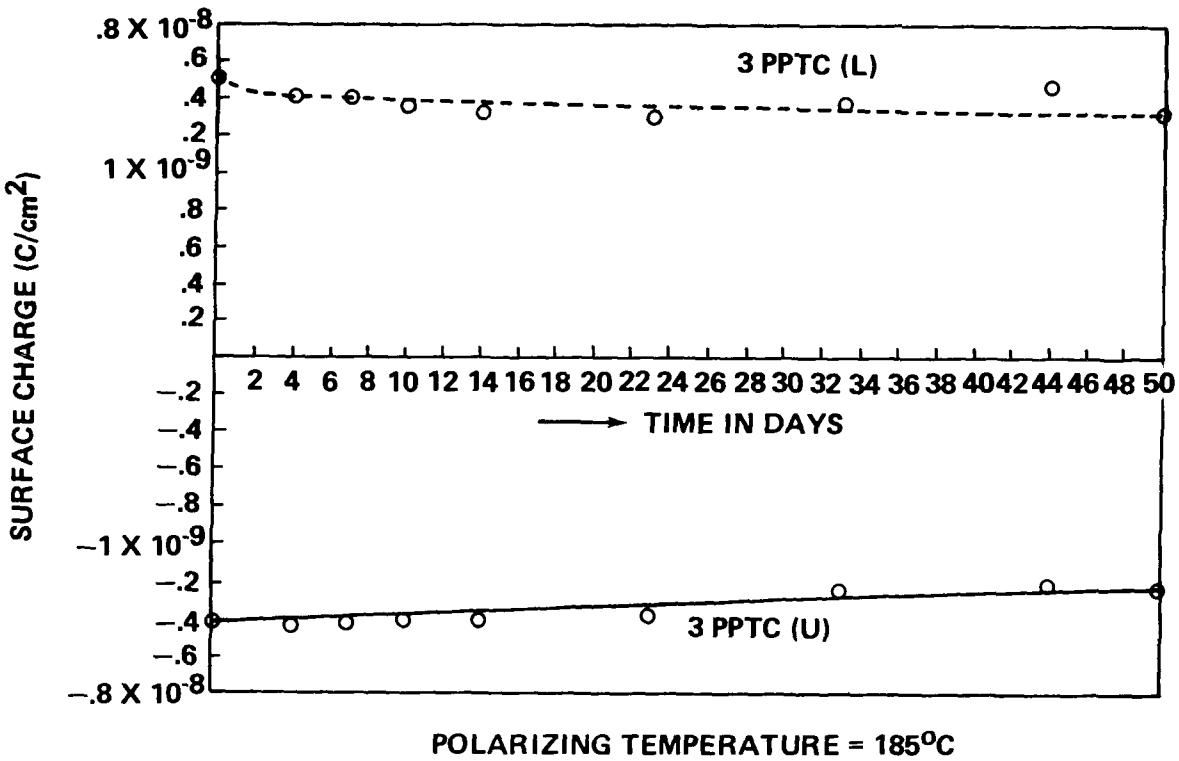


Figure 30. Surface charge decay characteristics of Tesla-coil charged polypropylene electrets. 3 refers to sample number. PP refers to polypropylene. TC refers to Tesla coil.

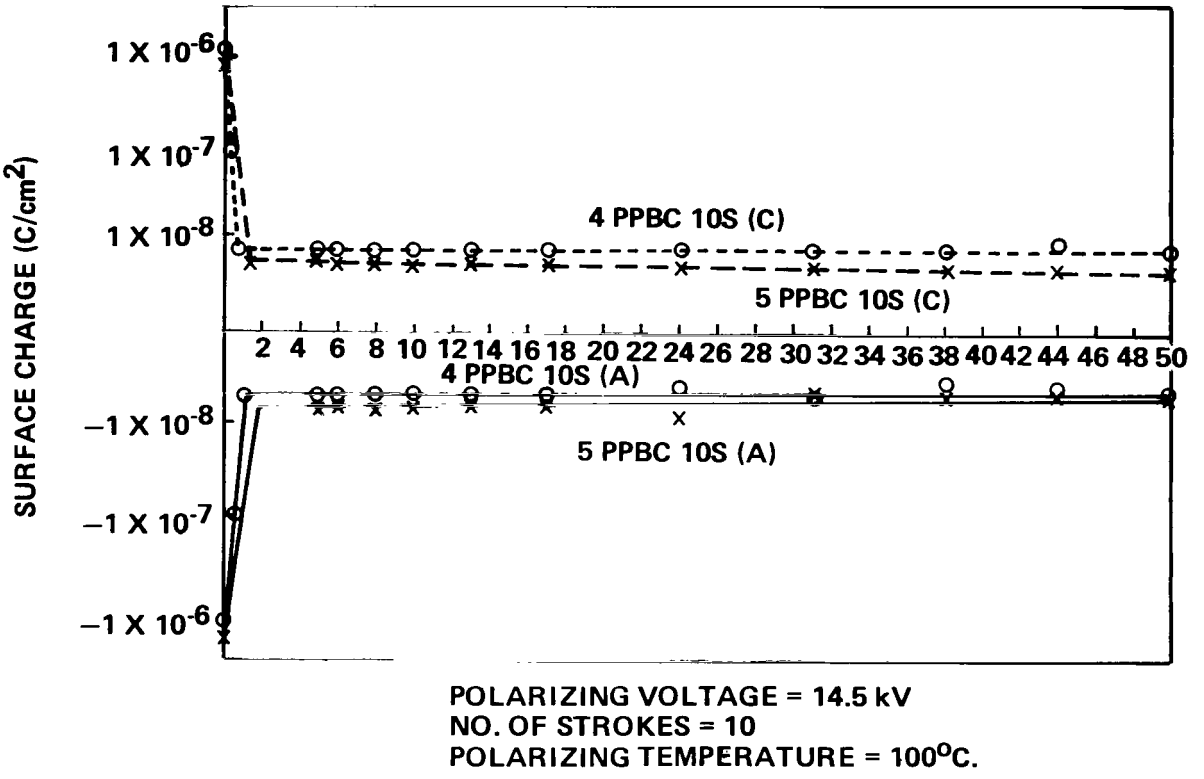


Figure 31. Surface charge decay characteristics of brush-corona charged polypropylene electrets. 4 and 5 refer to sample number. PP refers to polypropylene. BC10S refers to brush corona, 10 strokes.

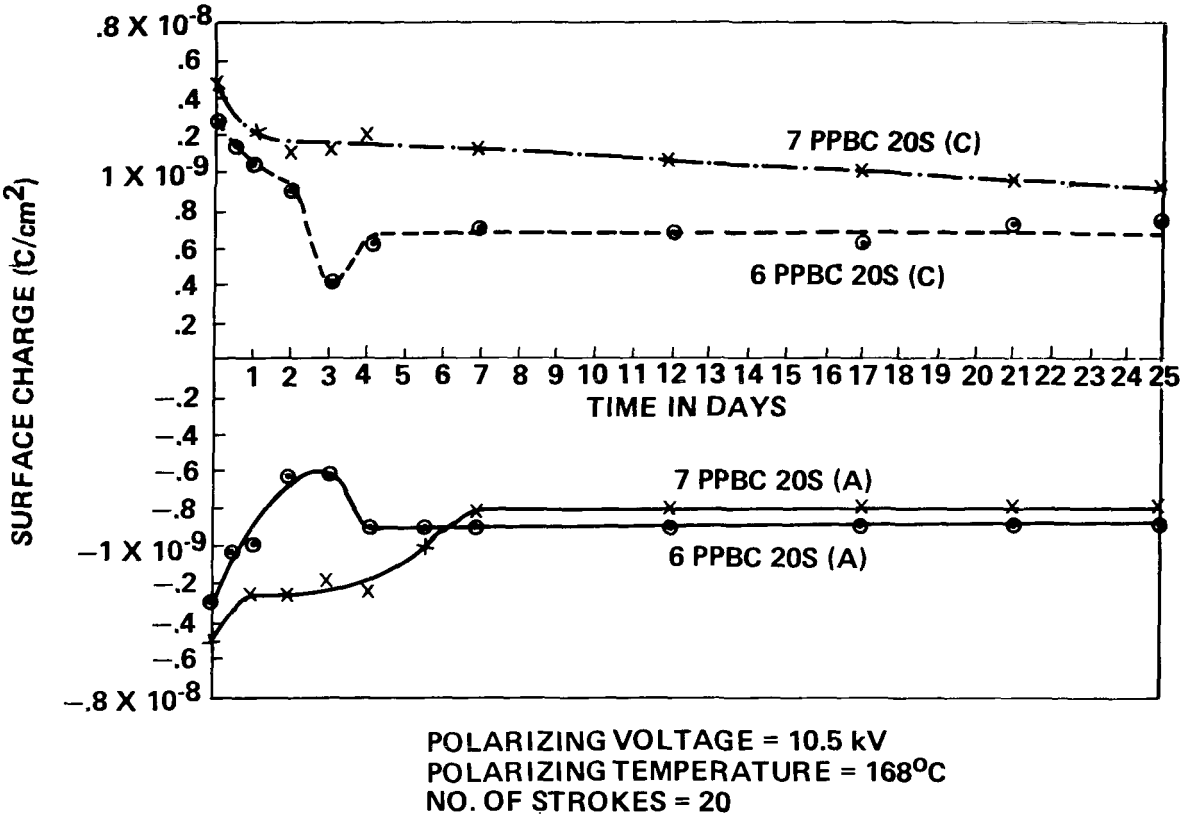


Figure 32. Surface charge decay characteristics of brush-corona charged polypropylene electrets. Nomenclature same as Figure 31.

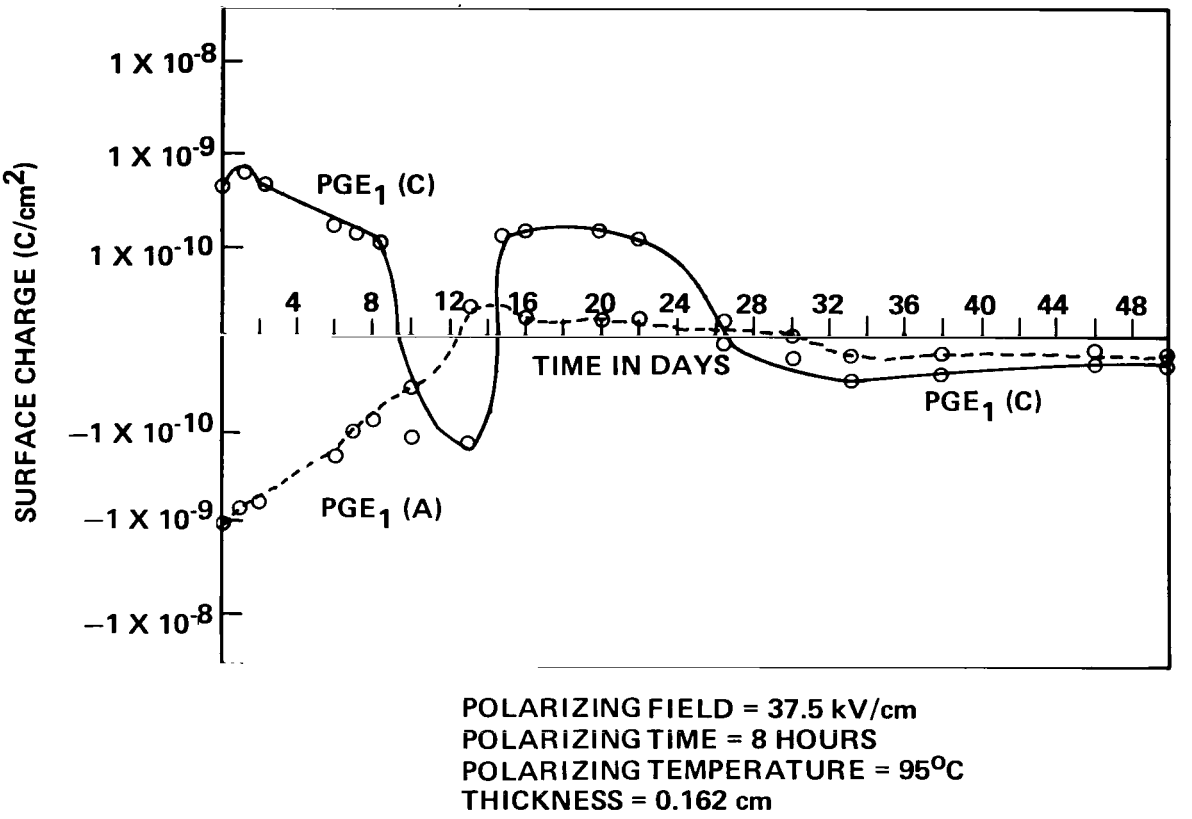


Figure 33. Surface charge decay characteristics of plexiglass (polymethyl methacrylate) thermoelectrets. PG refers to plexiglass. E_1 refers to electret sample number.

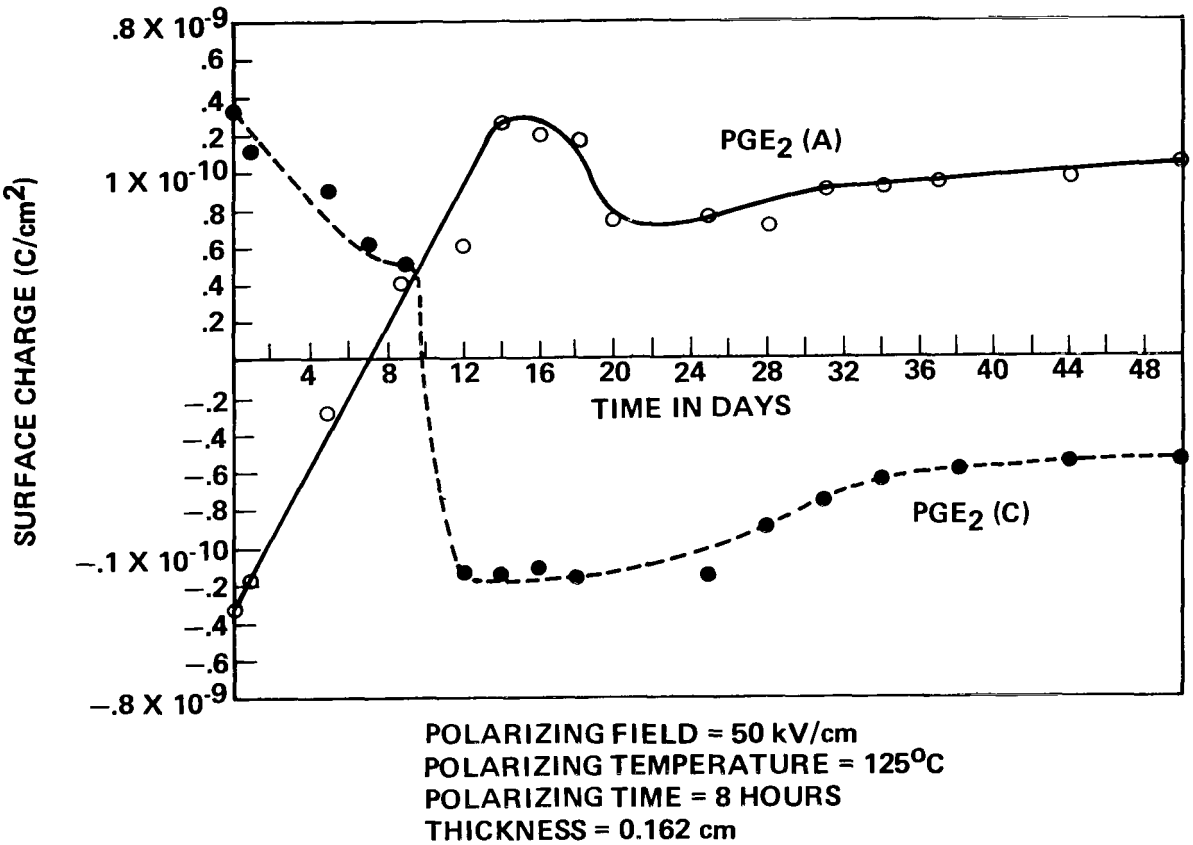
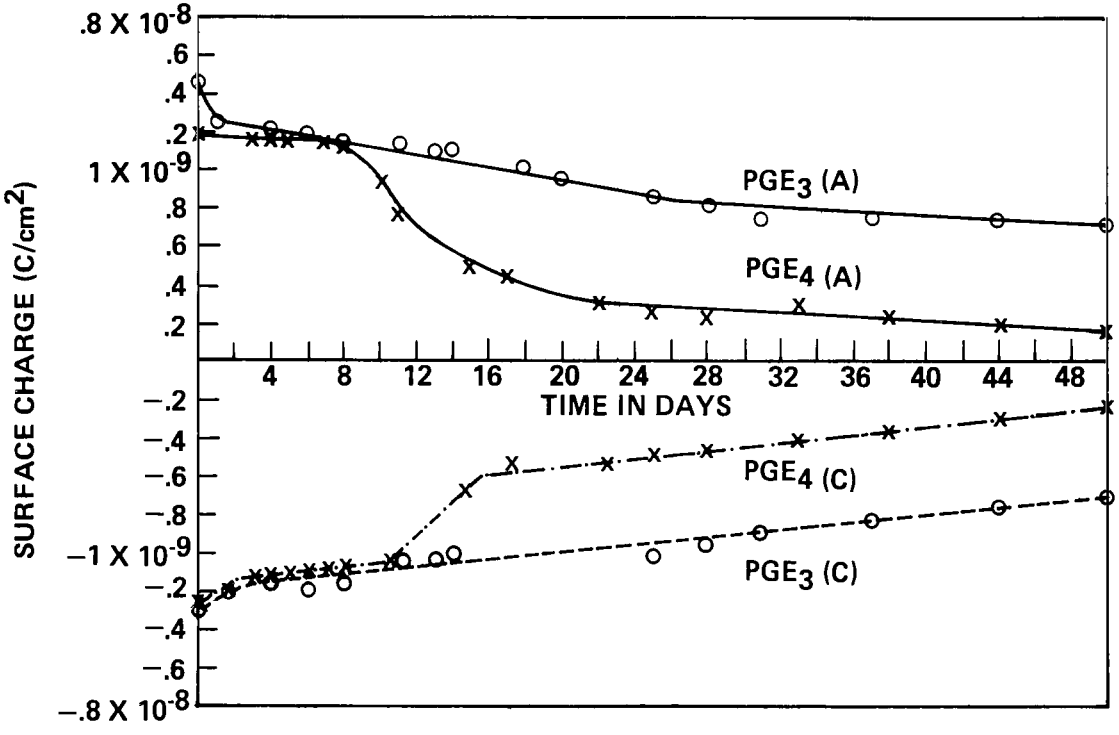


Figure 34. Surface charge decay characteristics of plexiglass thermoelectrets. Nomenclature same as Figure 33.



FOR PGE_3 POLARIZING FIELD = 50 kV/cm; POLARIZING TEMPERATURE = 150°C; POLARIZING TIME = 8 HOURS

FOR PGE_4 POLARIZING FIELD = 37.5 kV/cm; POLARIZING TEMPERATURE = 175°C; POLARIZING TIME = 8 HOURS

THICKNESS = 0.162 cm

Figure 35. Surface charge decay characteristics of plexiglass thermoelectrets (samples were kept between mica sheets to control spray charge from electrodes). PG refers to plexiglass. E_3 and E_4 refer to electret sample number.

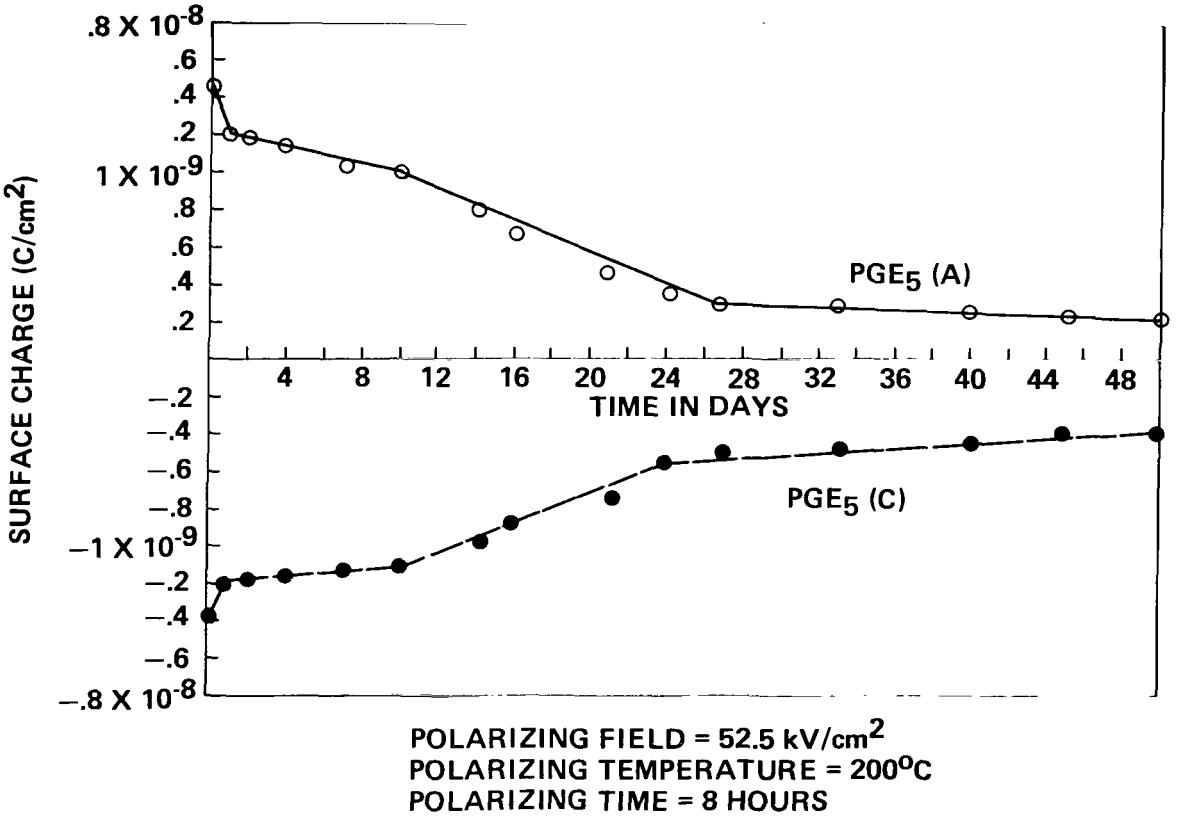


Figure 36. Charge decay characteristics of plexiglass thermoelectrets prepared between mica sheets. PG refers to plexiglass. E_5 refers to sample number.

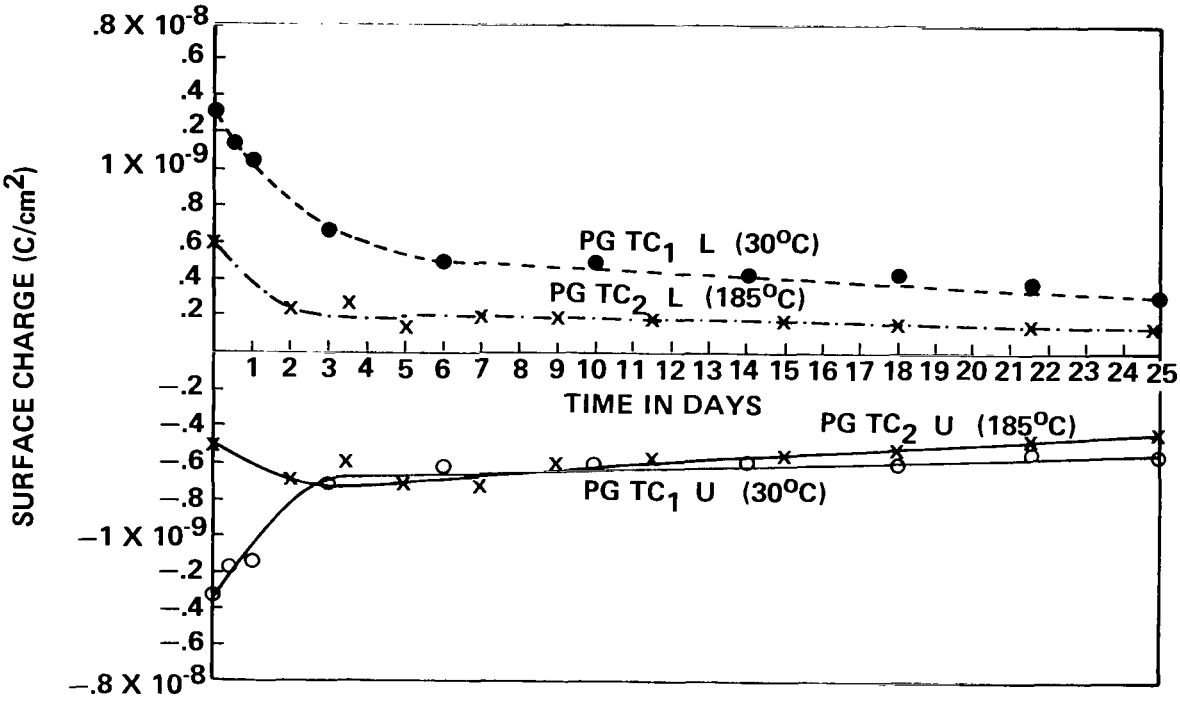


Figure 37. Charge decay characteristics of plexiglass electrets charged with Tesla coil. PG refers to plexiglass. TC refers to Tesla coil. 1 and 2 refer to sample number.

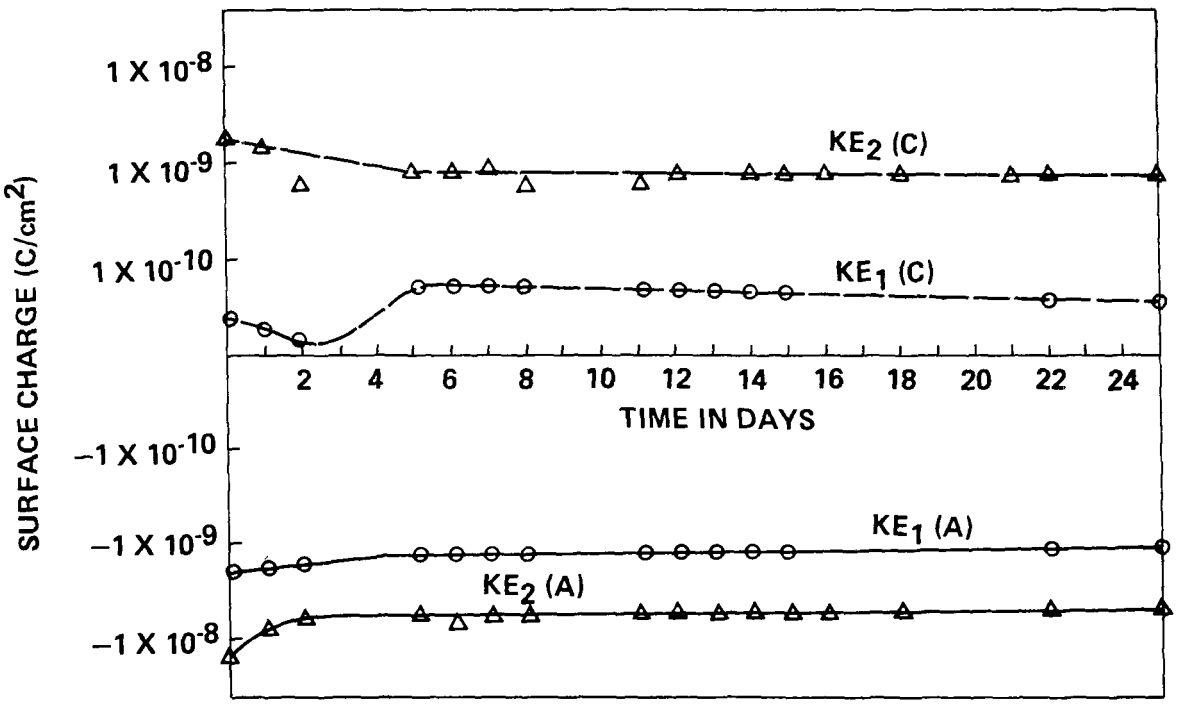
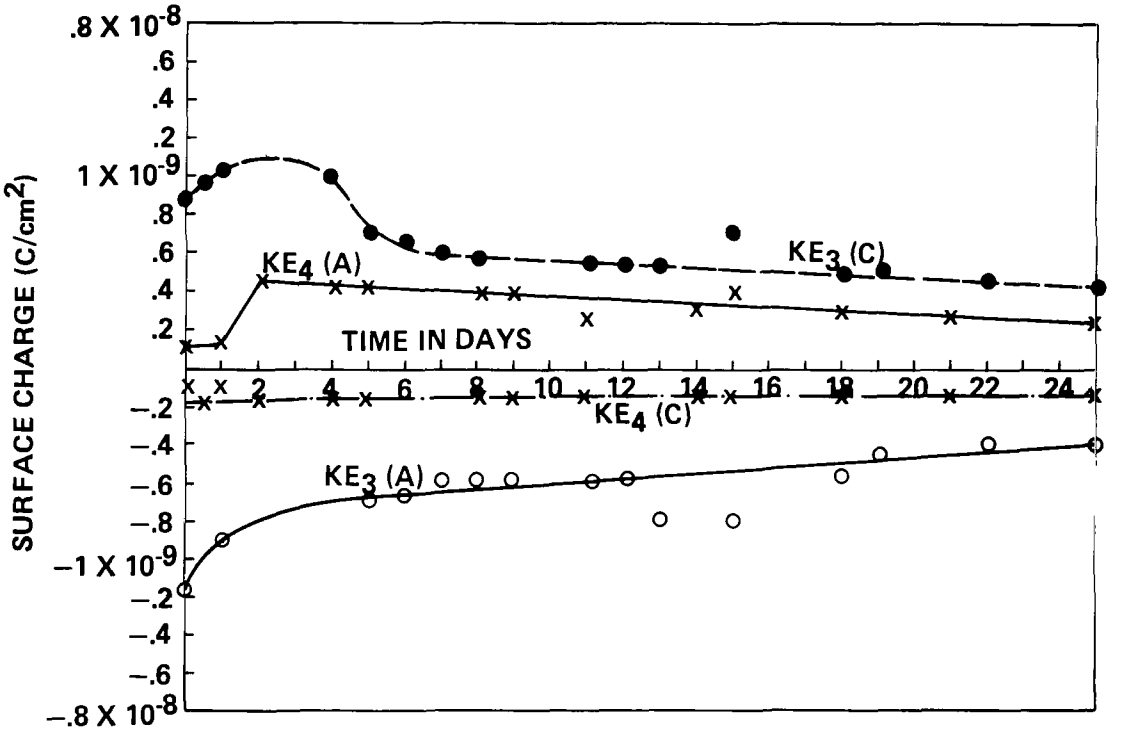


Figure 38. Charge decay characteristics of metal-impregnated Kapton thermoelectrets. The sample was prepared between mica sheets to prevent spray charge. K refers to Kapton. E_1 and E_2 refer to electret samples.



FOR KE_4, POLARIZING FIELD = 280 kV/cm
POLARIZING TEMPERATURE = 200°C
POLARIZING TIME = 8 HOURS

8 FLAT Cu STRIPS IN THE SAMPLE WERE CONNECTED TO THE +URE, AND THE UPPER AND LOWER SIDES OF THE SAMPLE WERE CONNECTED TO −URE.

FOR KE_3, POLARIZING FIELD = 420 kV/cm
POLARIZING TEMPERATURE = 200°C
POLARIZING TIME = 8 HOURS
THICKNESS = 0.25 m

(8 FLAT 0.5 cm WIDTH Cu ELECTRODES WERE SANDWICHED BETWEEN THE POLYMER FILMS) BETWEEN MICA SHEETS

Figure 39. Charge decay characteristics of metal-impregnated Kapton thermoelectrets. K refers to Kapton. E_3 and E_4 refer to electret sample number.

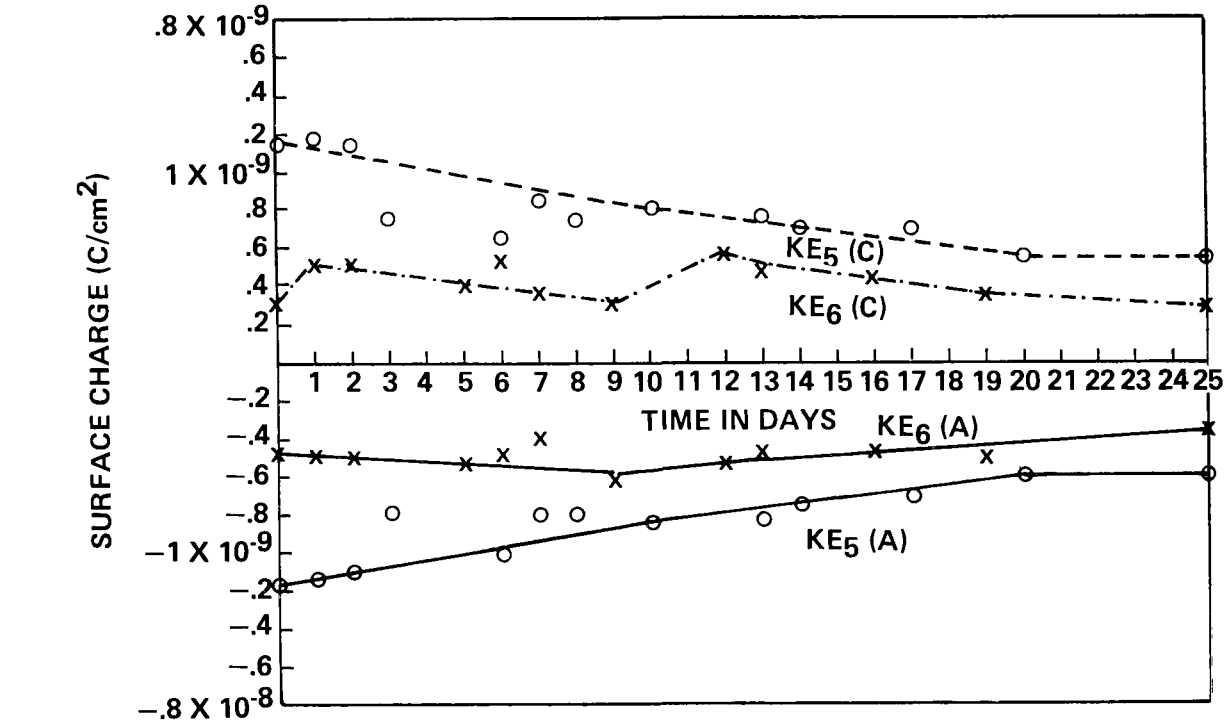


Figure 40. Charge decay characteristics of metal-impregnated Kapton thermoelectrets. Nomenclature same as Figure 39.

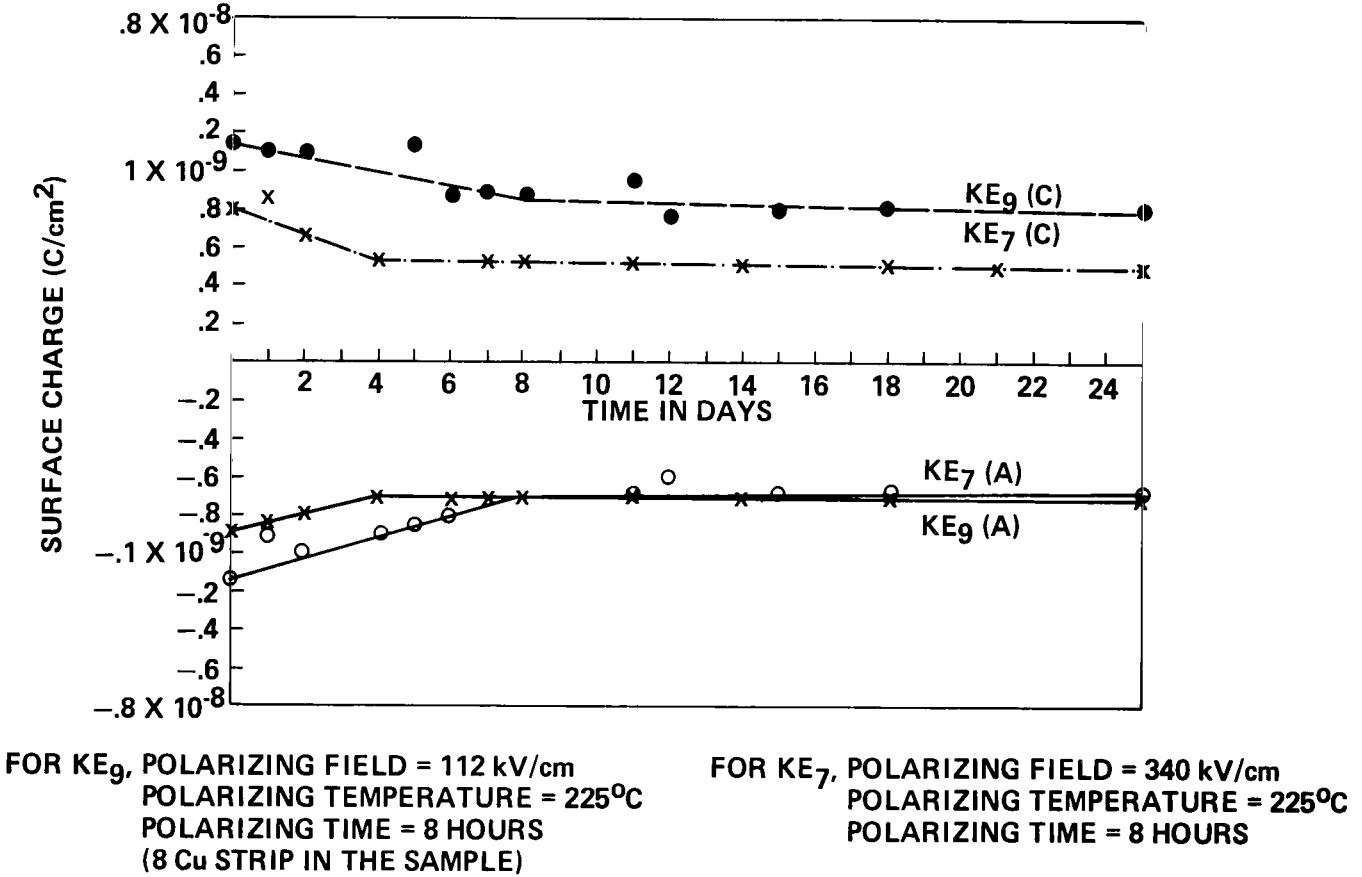


Figure 41. Charge decay characteristics of metal-impregnated (8 strips) Kapton thermoelectrets (between mica sheets). Nomenclature same as Figure 39.

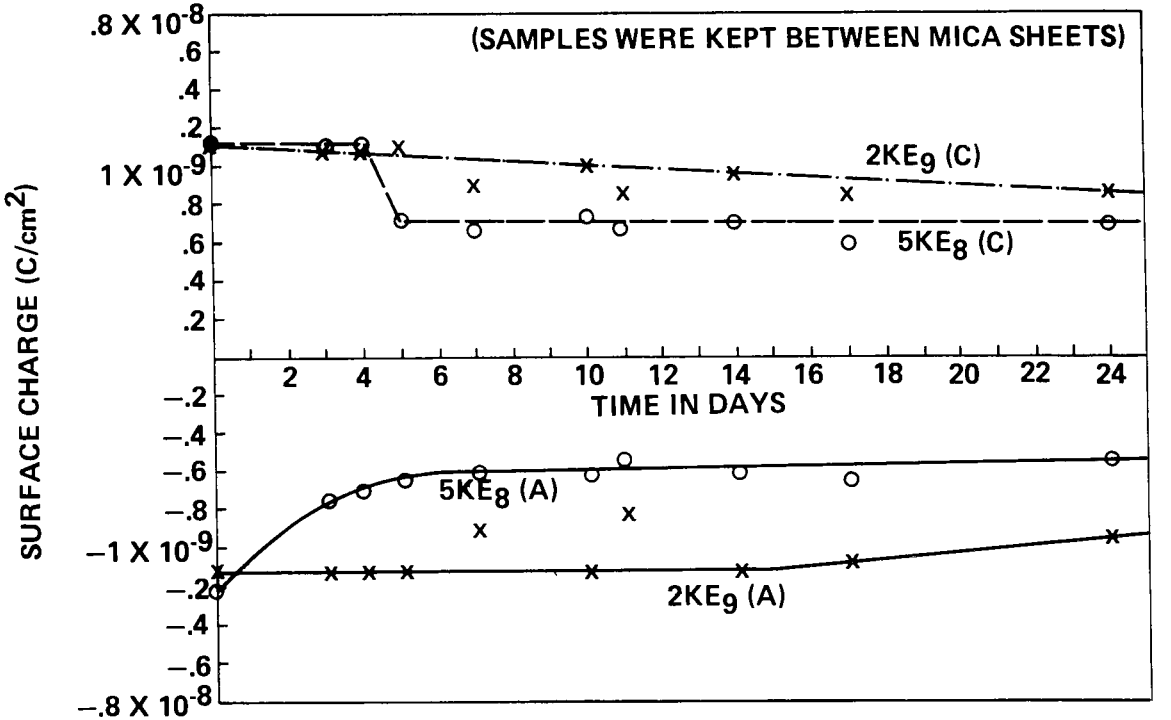
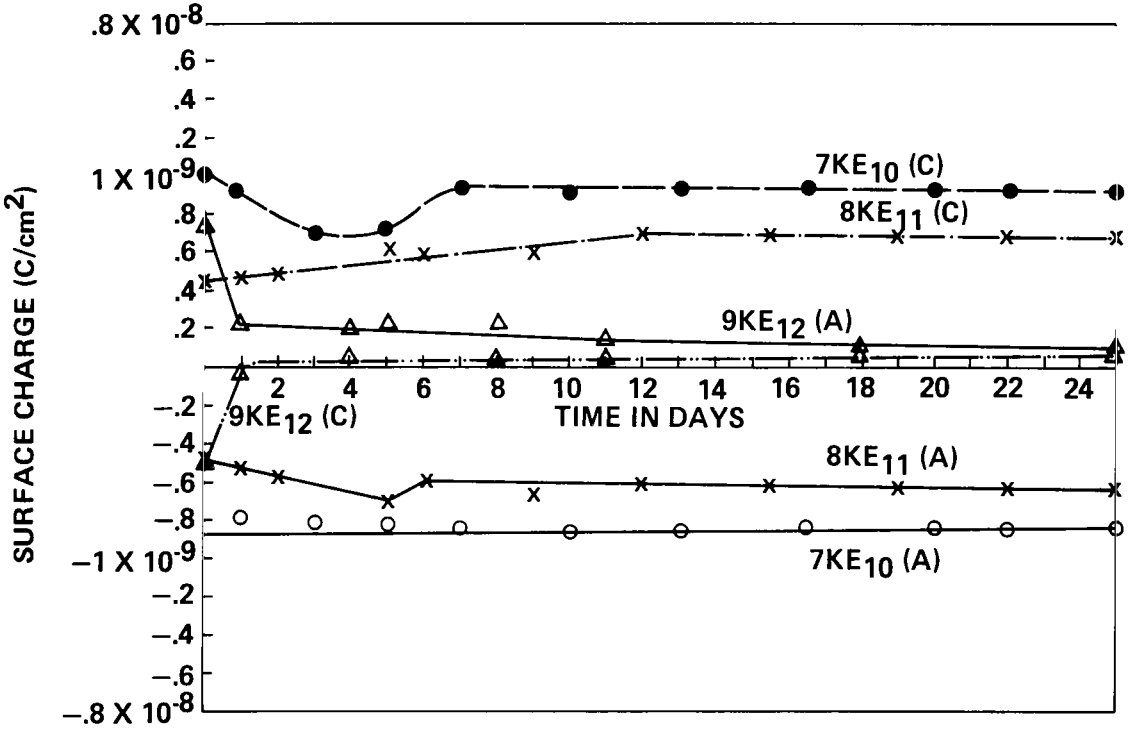


Figure 42. Charge decay characteristics of metal-impregnated Kapton thermoelectrets. 2 and 5 refer to electrets. K refers to Kapton. E_8 and E_9 refer to electret samples.



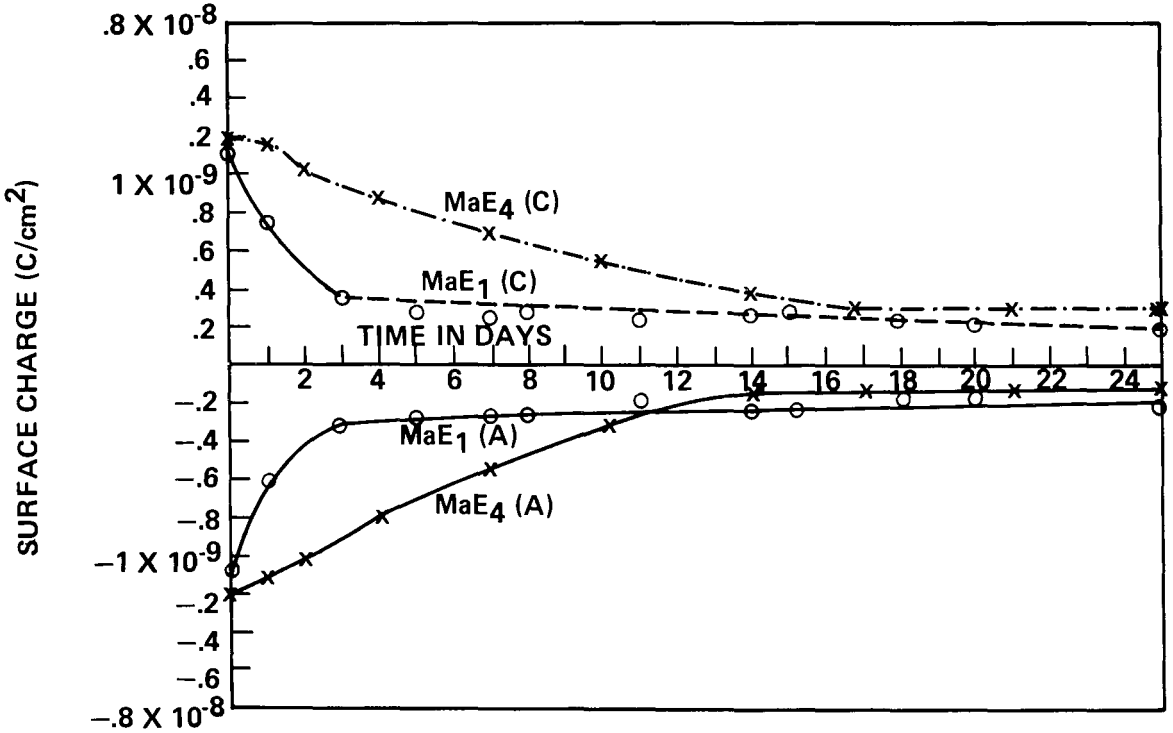
FOR $9KE_{12}$, POLARIZING FIELD = 30 kV/cm
POLARIZING TEMPERATURE = 225°C
POLARIZING TIME = 8 HOURS
(8 Cu ELECTRODES BETWEEN MICA SHEETS)

FOR $8KE_{11}$, POLARIZING FIELD = 60 kV/cm
POLARIZING TEMPERATURE = 225°C
POLARIZING TIME = 8 HOURS
(8 Cu FLAT ELECTRODES INSIDE THE SAMPLE)

FOR $7KE_{10}$, POLARIZING FIELD = 88 kV/cm
POLARIZING TEMPERATURE = 225°C
POLARIZING TIME = 8 HOURS

8 METAL STRIPS IN THE SAMPLE AND THE SAMPLE WERE KEPT BETWEEN MICA SHEETS.

Figure 43. Charge decay characteristics of metal-impregnated Kapton thermoelectrets. Nomenclature same as Figure 42.



FOR MaE_4: POLARIZING VOLTAGE = 14 kV
POLARIZING TEMPERATURE = 160°C
POLARIZING TIME = 8 HOURS
THICKNESS = 0.3 mm

FOR MaE_1, POLARIZING VOLTAGE = 7.7 kV
POLARIZING TEMPERATURE = 160°C
POLARIZING TIME = 8 HOURS
THICKNESS = 0.3 mm

Figure 44. Charge decay characteristics of mica electrets. Ma refers to mica. E_1 and E_4 refer to electret sample number.

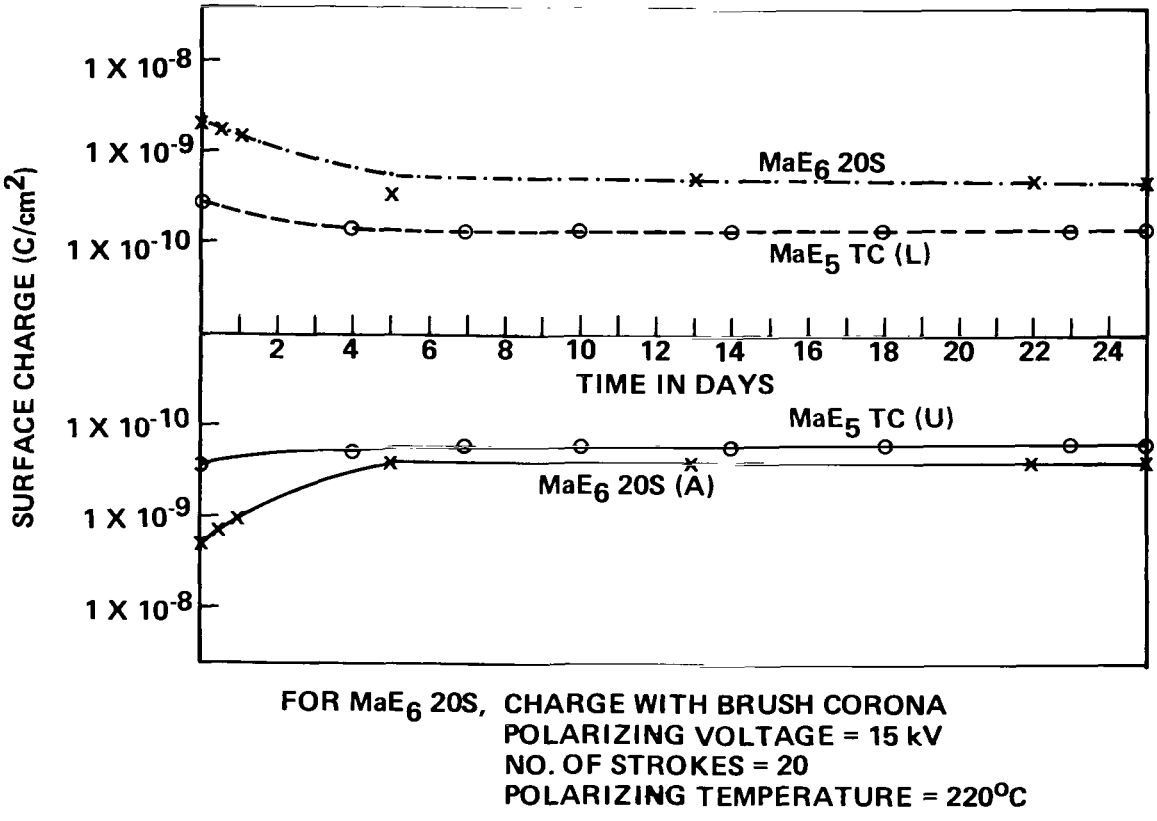


Figure 45. Charge decay characteristics of mica electrets charged with brush corona and Tesla coil. MaE_5 is charged with Tesla coil at 200°C.

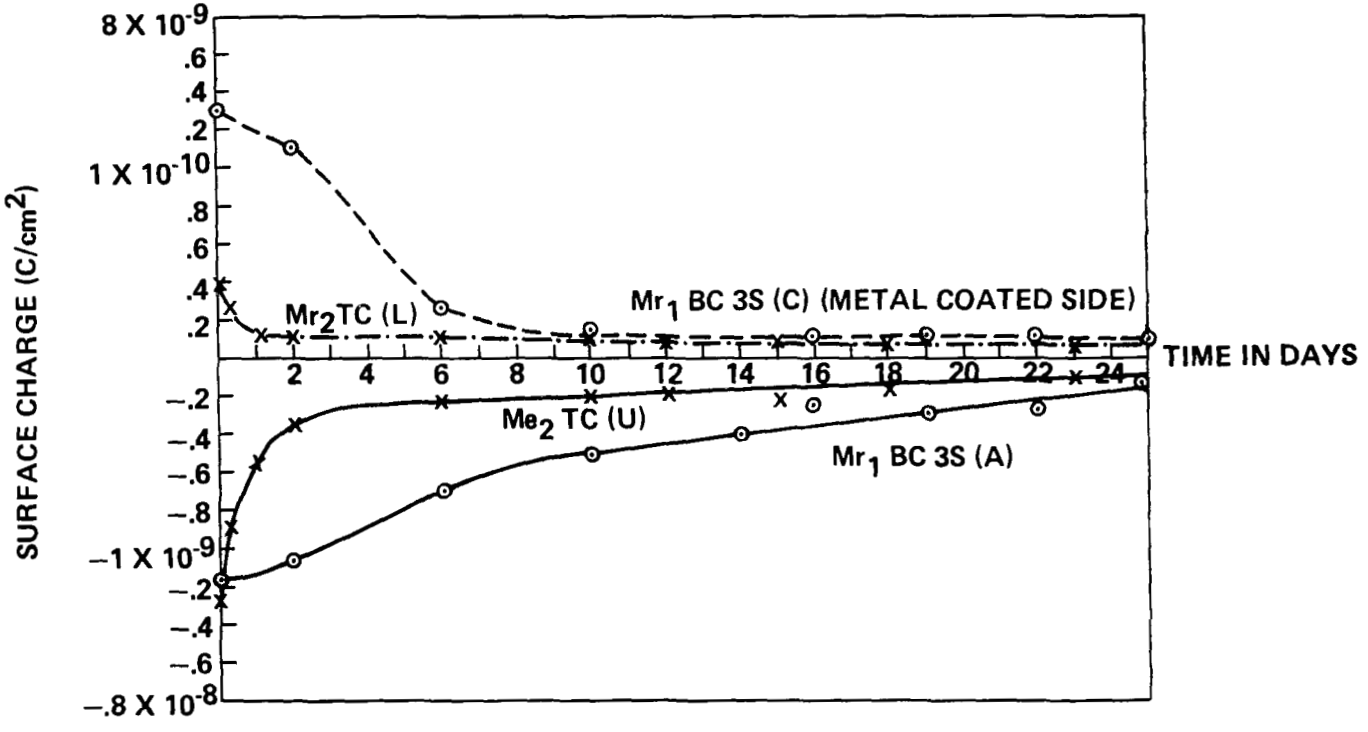


Figure 46. Charge decay characteristics of Mylar electret charged with brush corona and Tesla coil. Mr refers to Mylar.

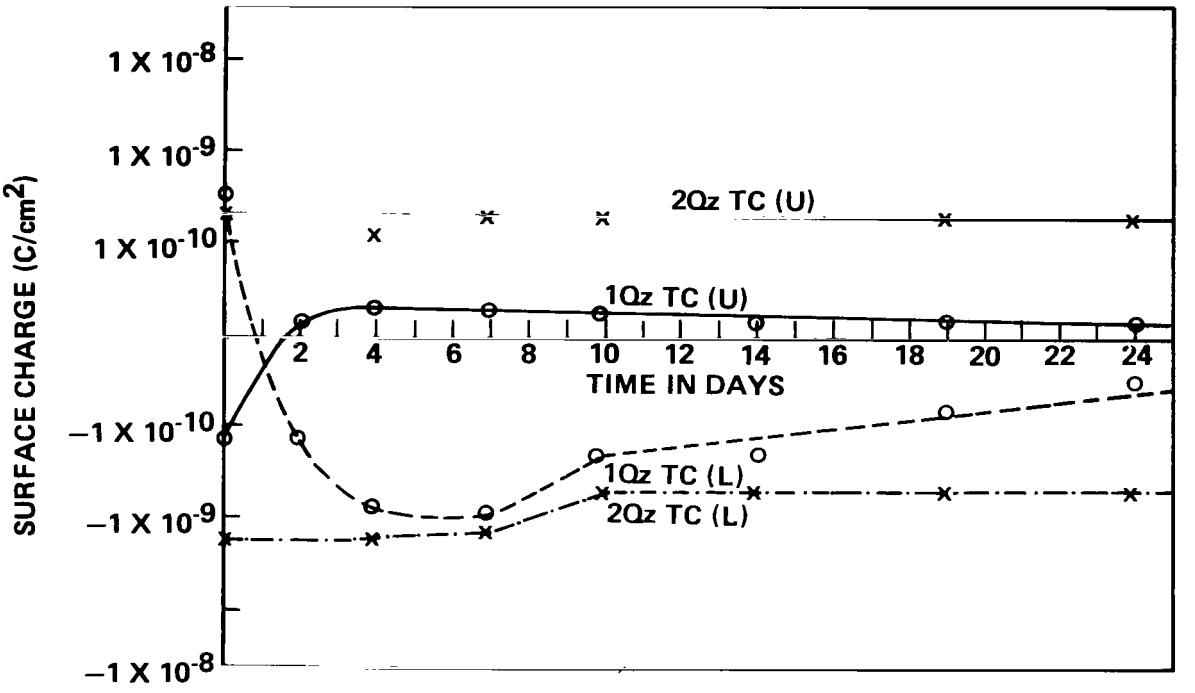


Figure 47. Charge decay characteristics of fused quartz disc electrets. 1 and 2 refer to sample number. Qz refers to quartz. TC refers to Tesla coil.

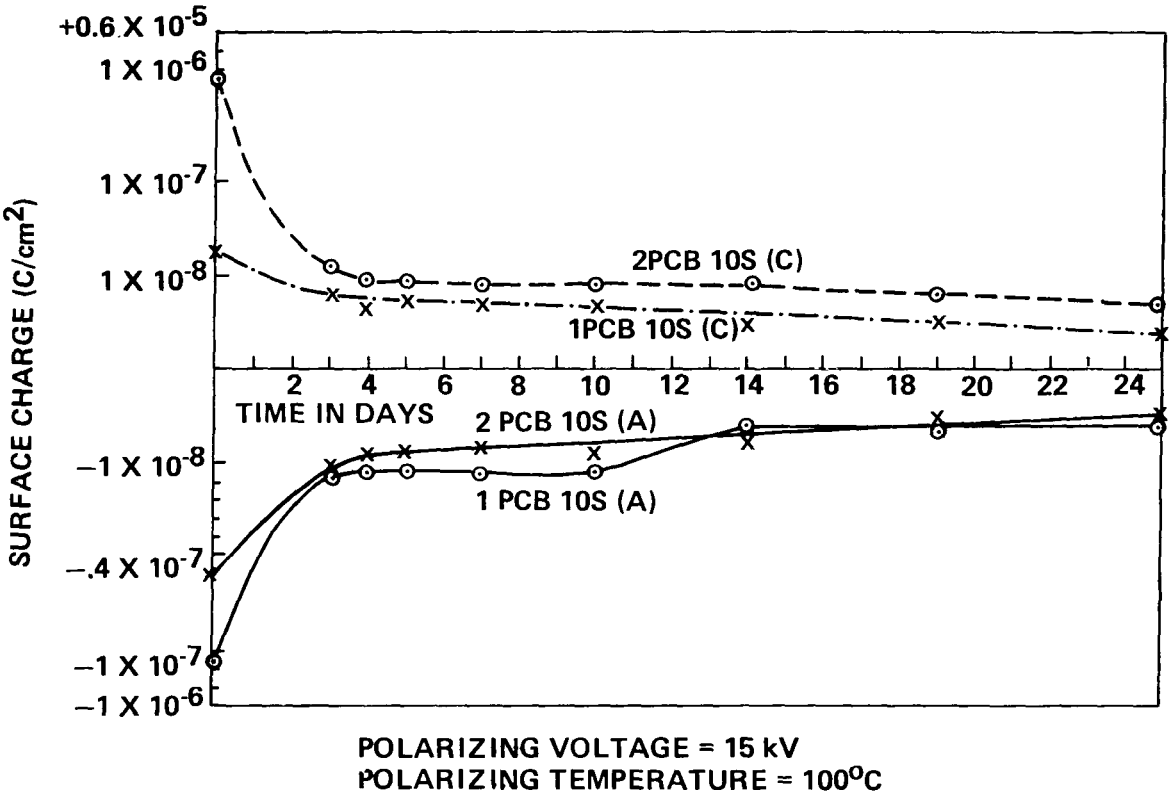


Figure 48. Charge decay characteristics of polycarbonate electret charged with brush corona. 1 and 2 refer to sample numbers. PC refers to polycarbonate. B10S refers to 10 strokes brush corona.

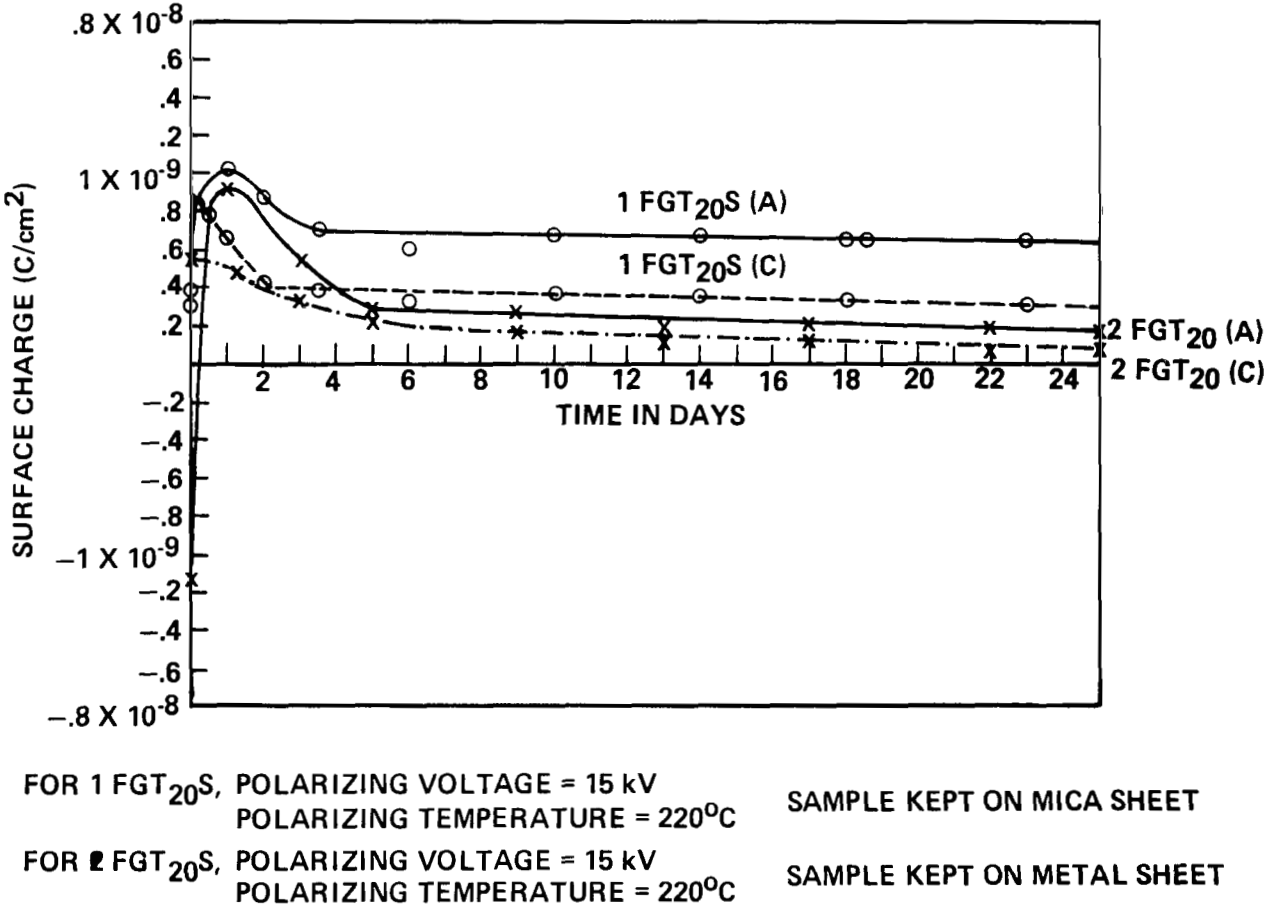


Figure 49. Charge decay characteristics of Teflon-coated fiber glass electrets charged with brush corona. 1 and 2 refer to sample number. FGT refers to Teflon-coated fiber glass cloth. 20 refers to brush corona, 20 strokes.

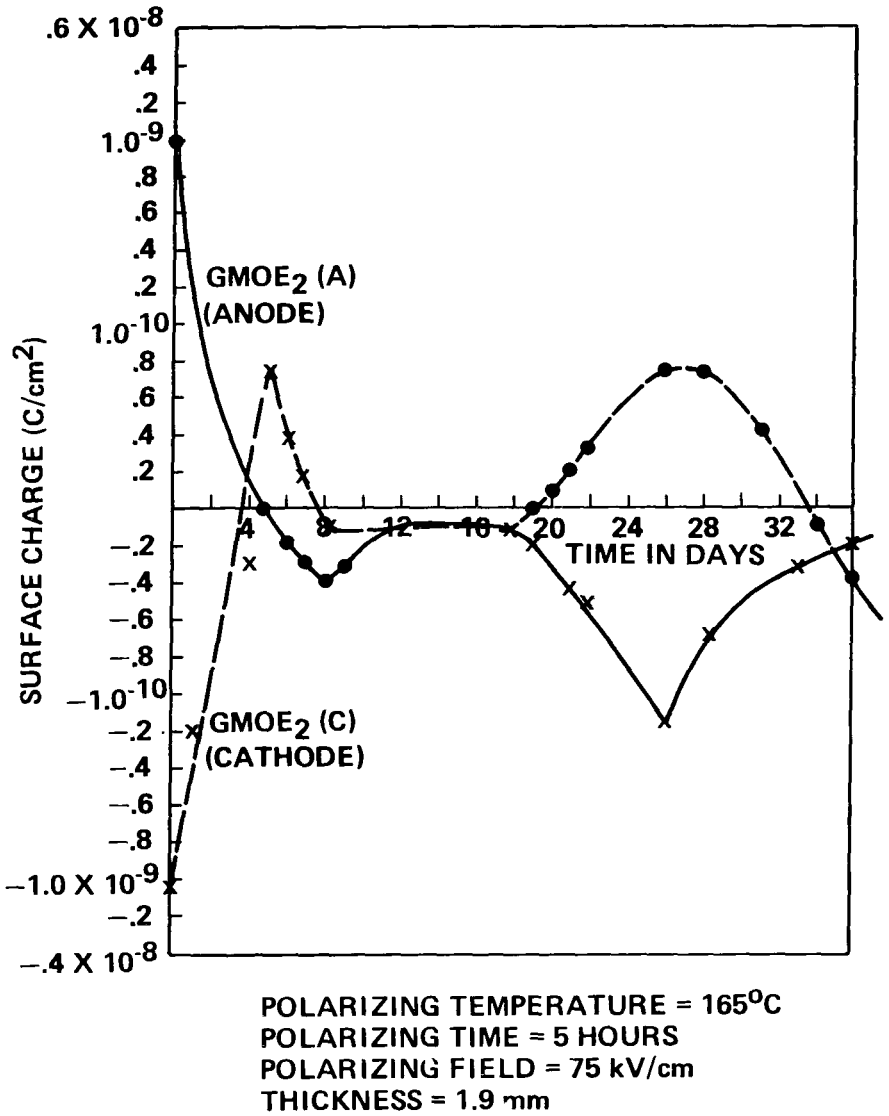


Figure 50. $GMOE_2$ charge decay characteristics of GMO crystal electrets. GMO refers to gadolinium molybdate. E_2 refers to electret sample number.

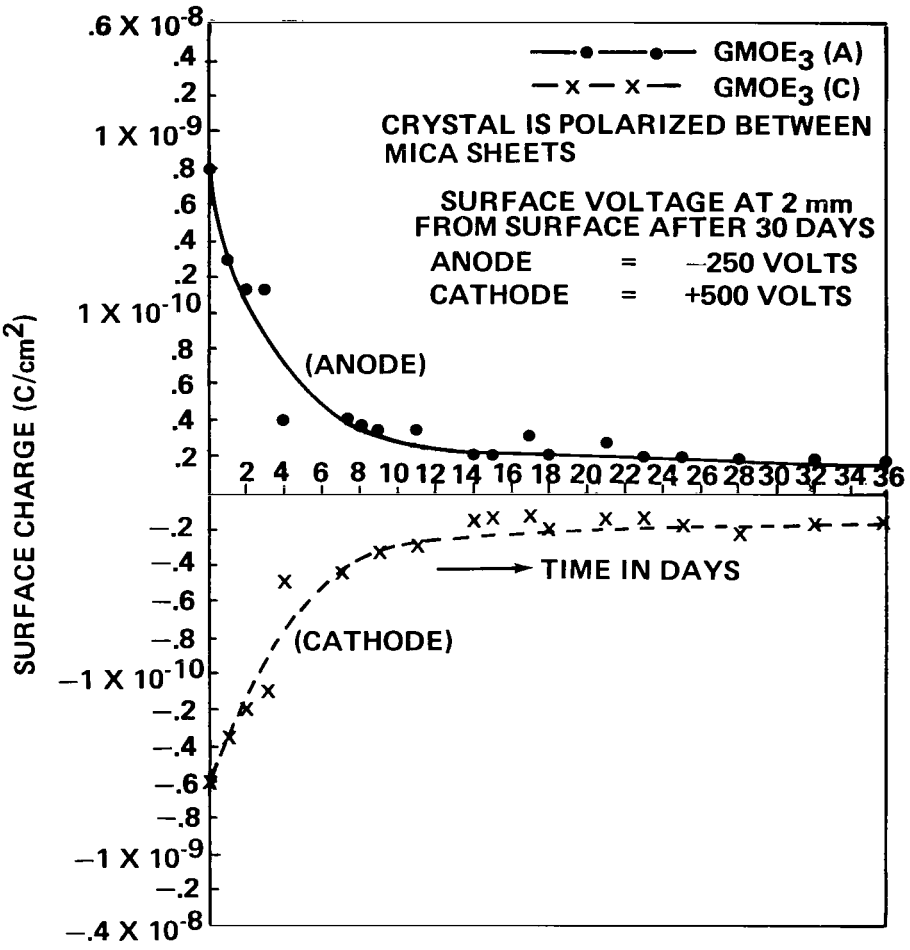


Figure 51. $GMOE_3$ charge decay characteristics of GMO electrets. Nomenclature same as Figure 50.

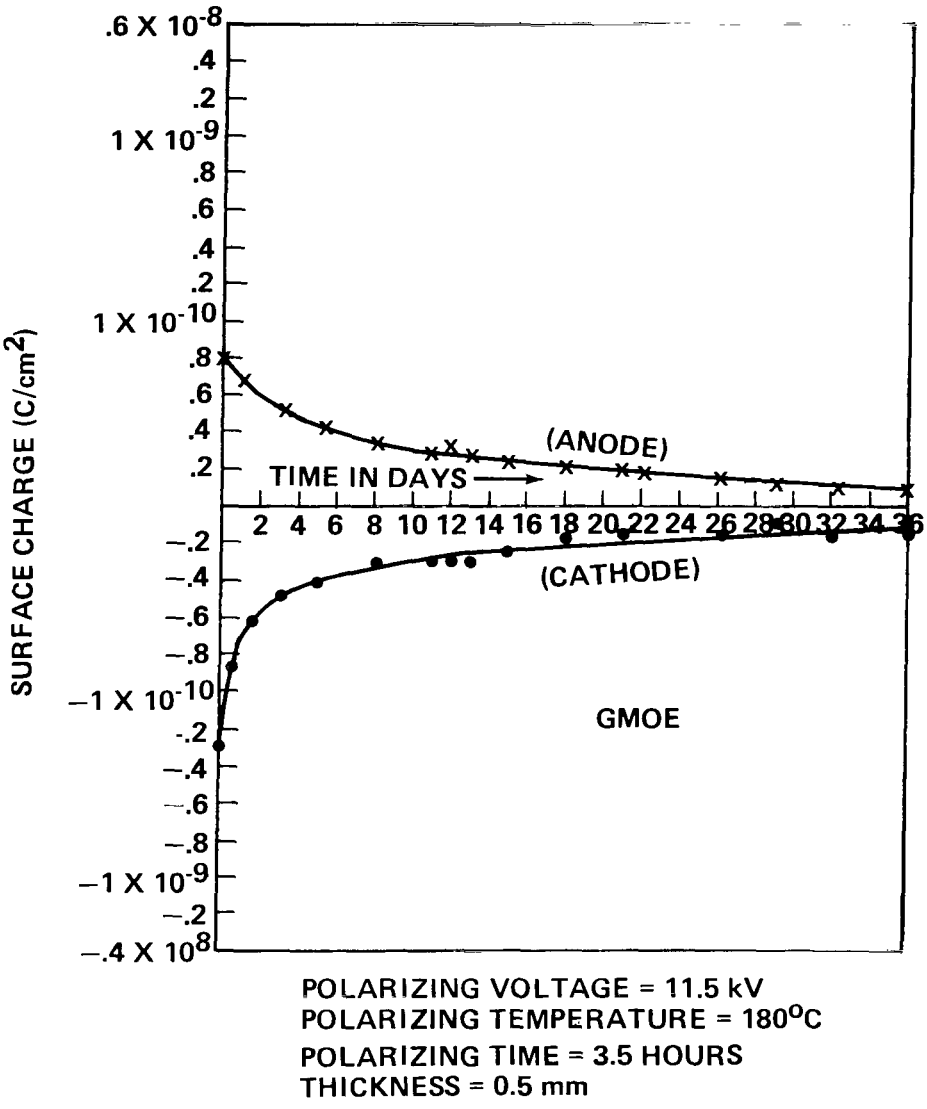


Figure 52. Charge decay characteristics of GMO electrets polarized between Teflon foil. Nomenclature same as Figure 50.

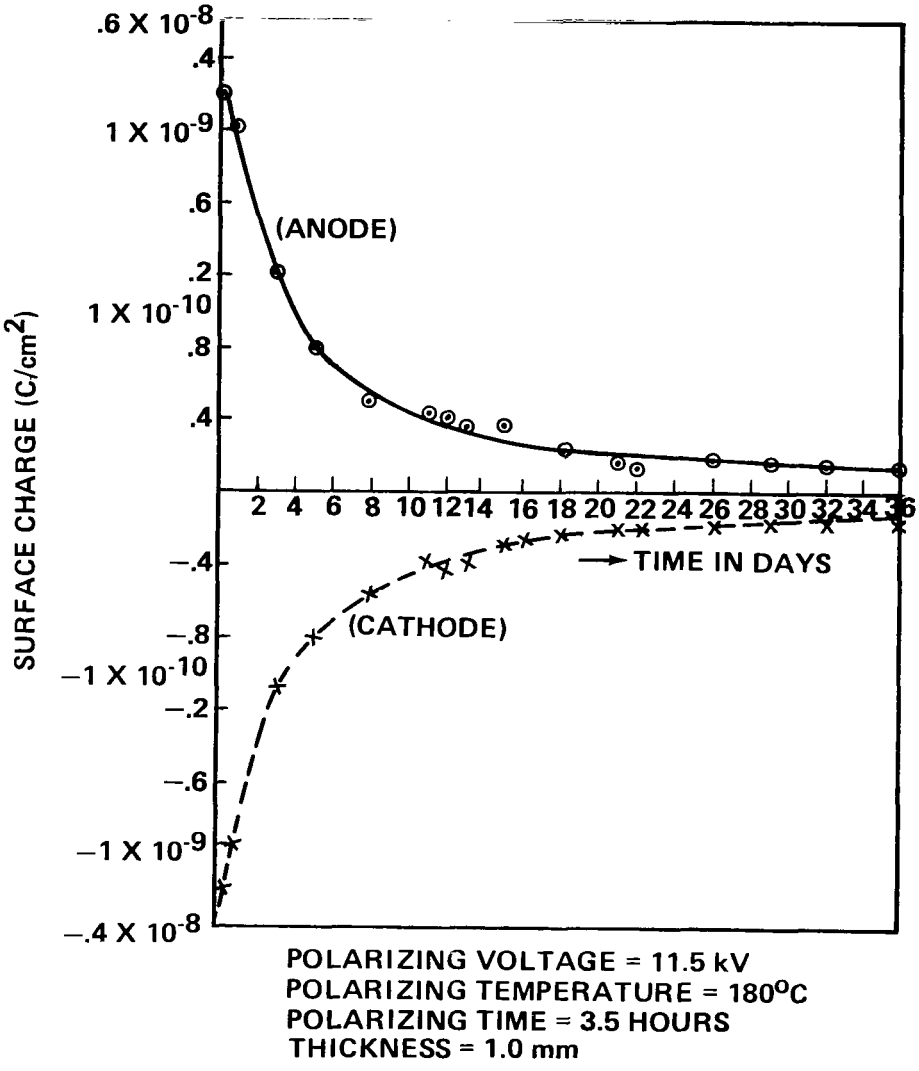


Figure 53. $GMOE_7$ charge decay characteristics of GMO electrets polarized between Teflon foil. Nomenclature same as Figure 50.

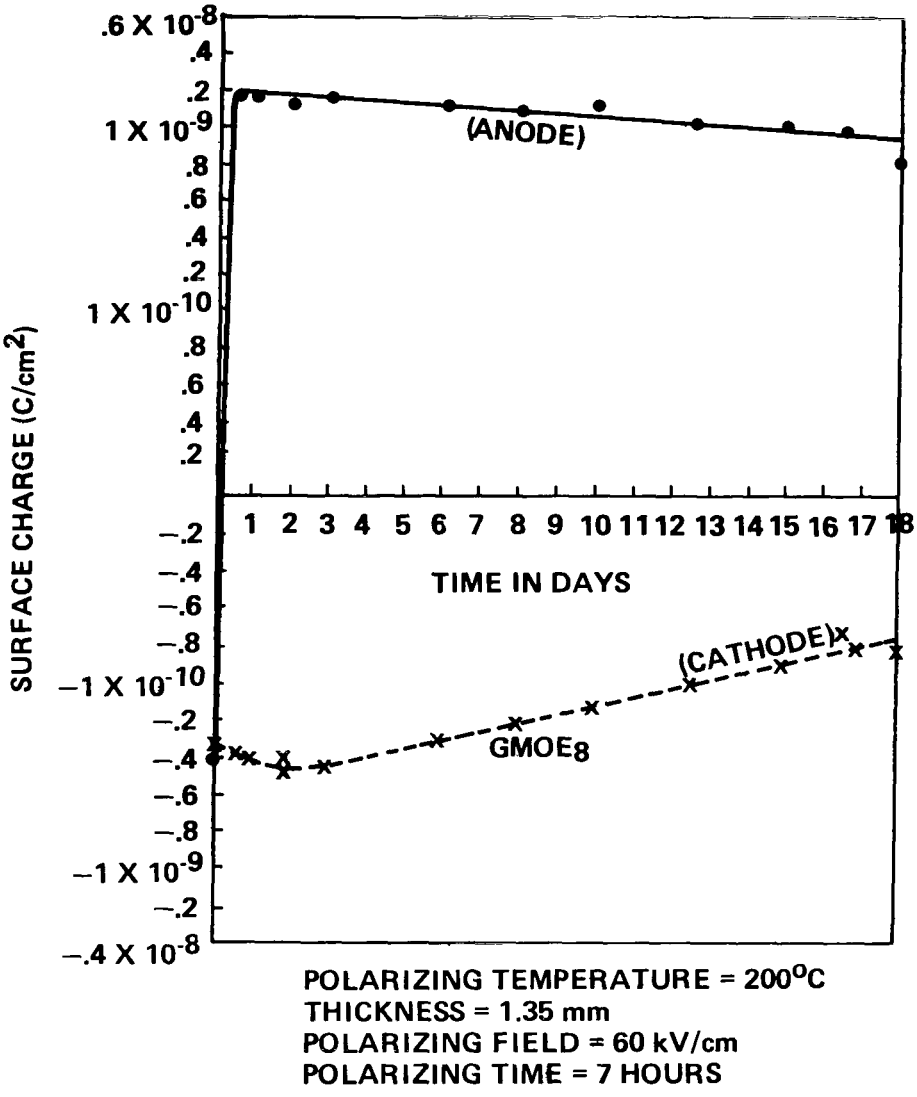


Figure 54. Charge decay characteristics of GMO single crystal electret. Nomenclature same as Figure 50.

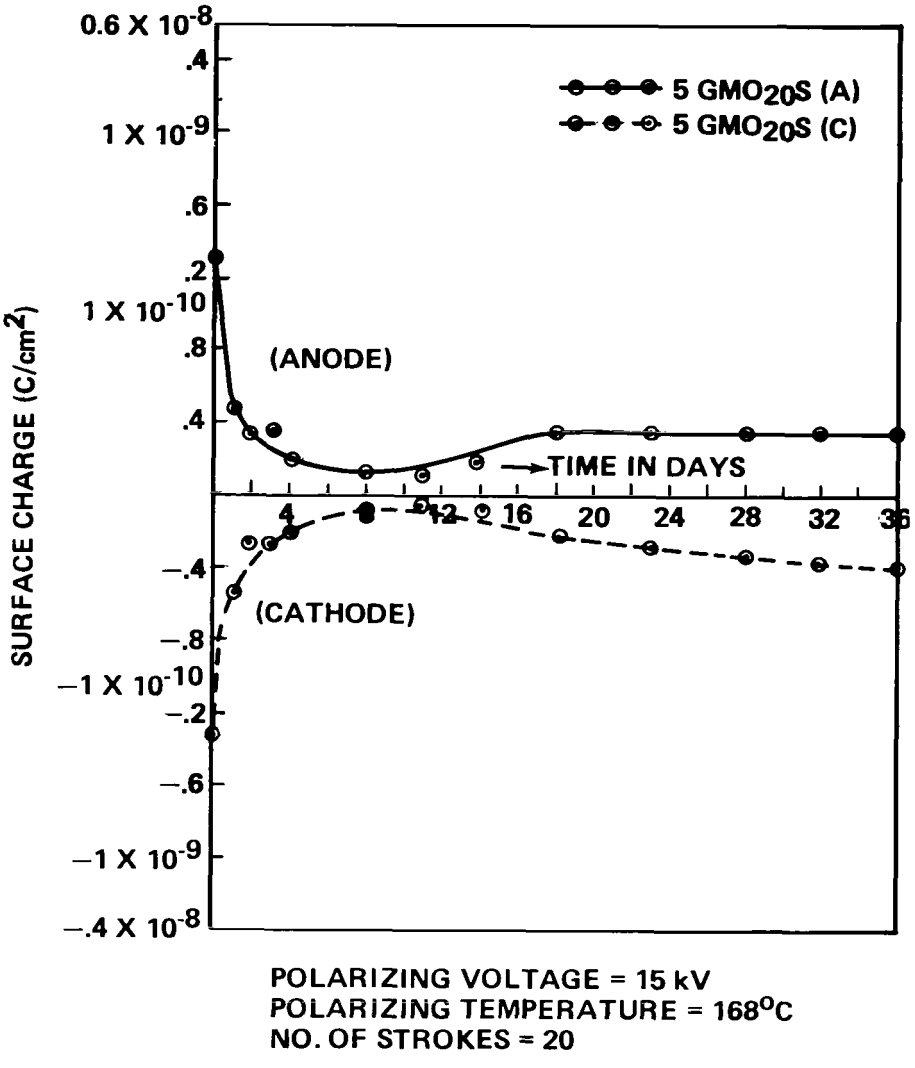


Figure 55. 5 $GMO_{20}S$ charge decay characteristics of corona-charged GMO electrets. 5 refers to sample number. GMO refers to gadolinium molybdate. $_{20}S$ refers to brush corona, 20 strokes.

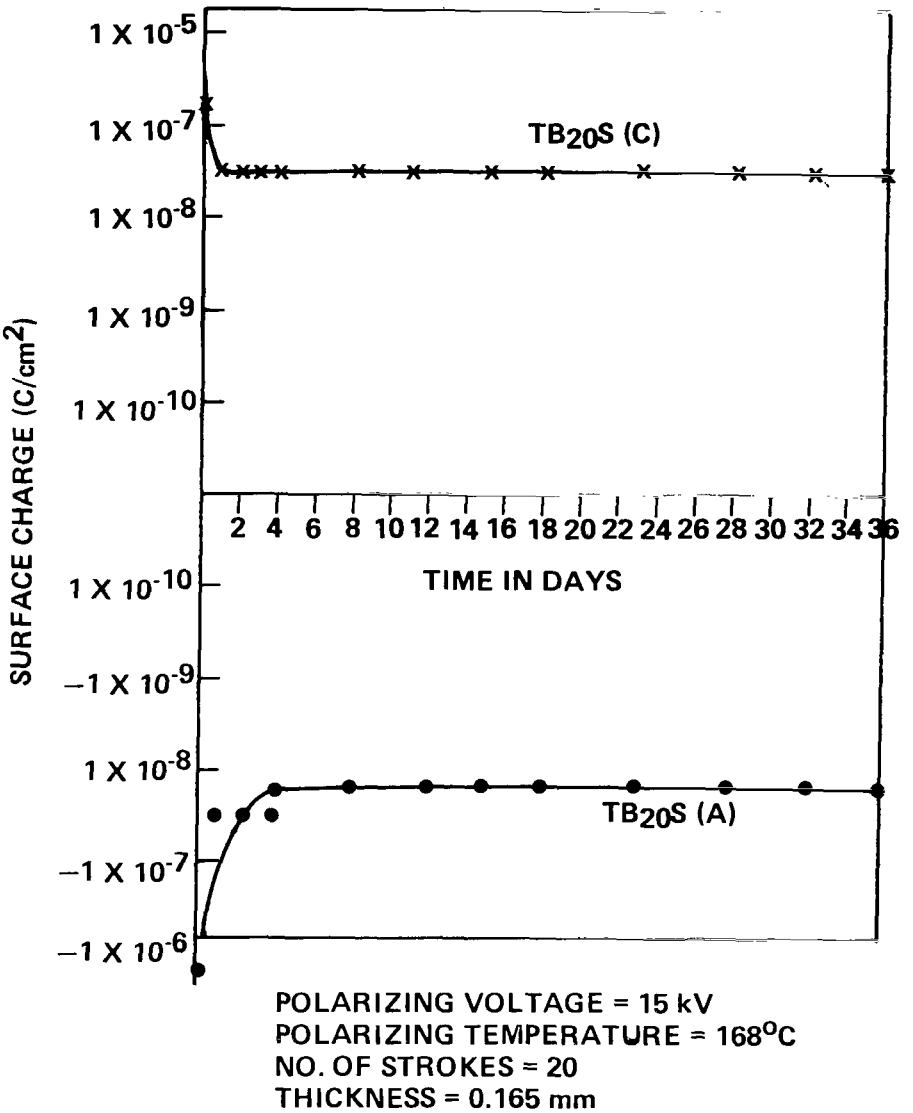


Figure 56. $TB_{20}S$ charge decay characteristics of corona-charged Teflon electret. T refers to Teflon. $B_{20}S$ refers to brush corona, 20 strokes.

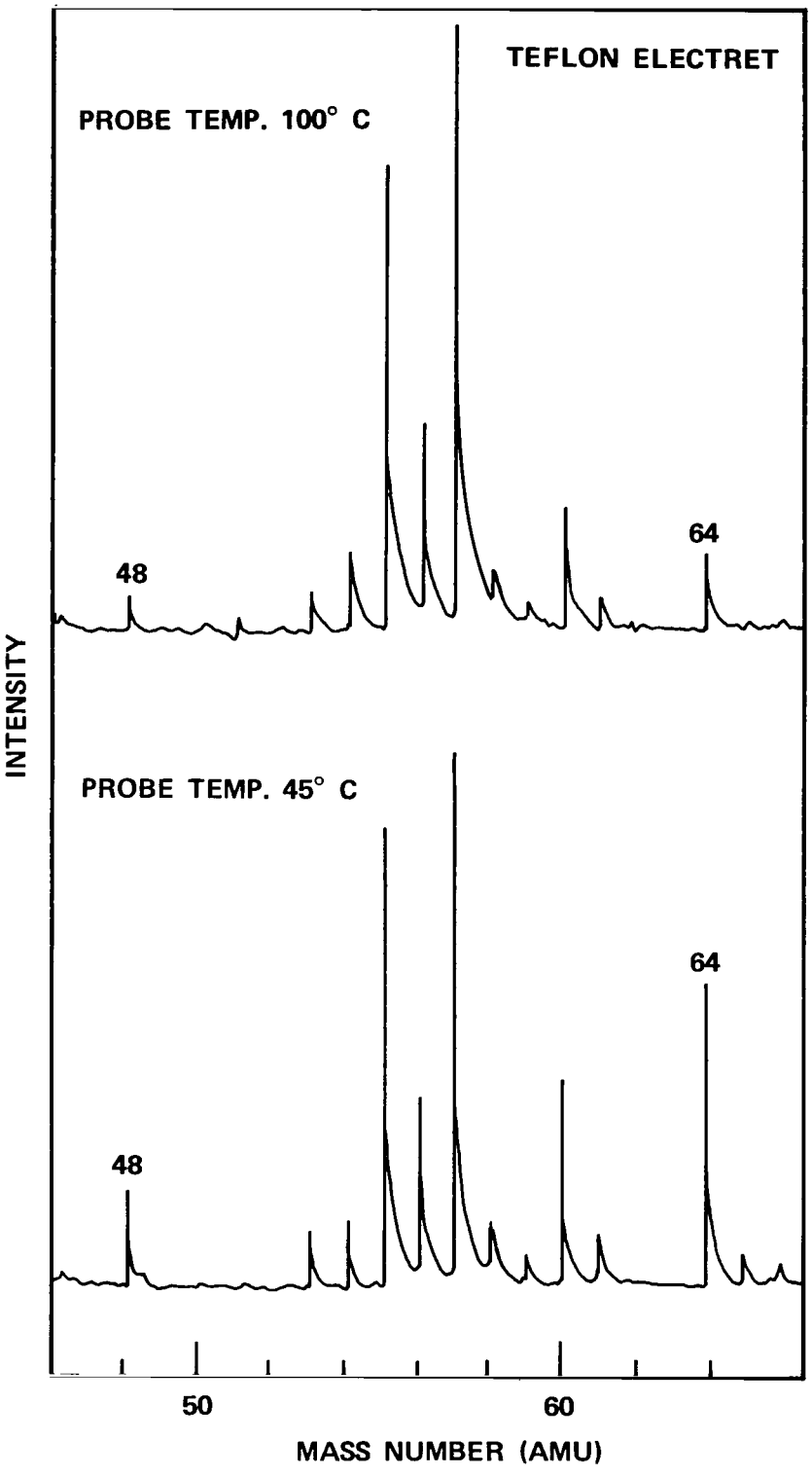


Figure 57. Major peaks of SO_2 at 48 and 64 AMU from a Teflon electret at 45°C and 100°C.

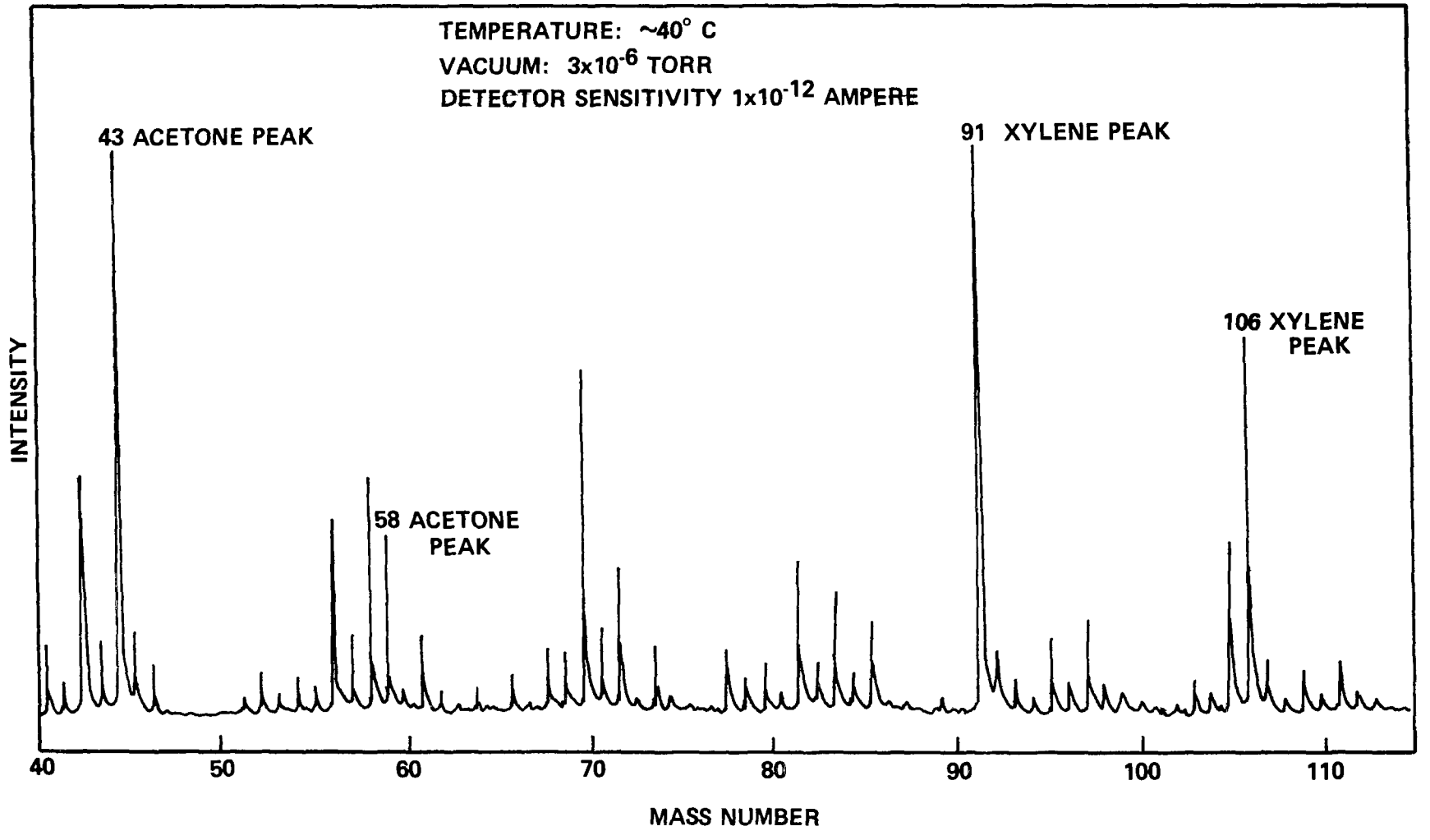


Figure 58. Major peaks of acetone and xylene from a Teflon electret exposed to the vapors of a mixture of equal volumes of acetone and xylene.

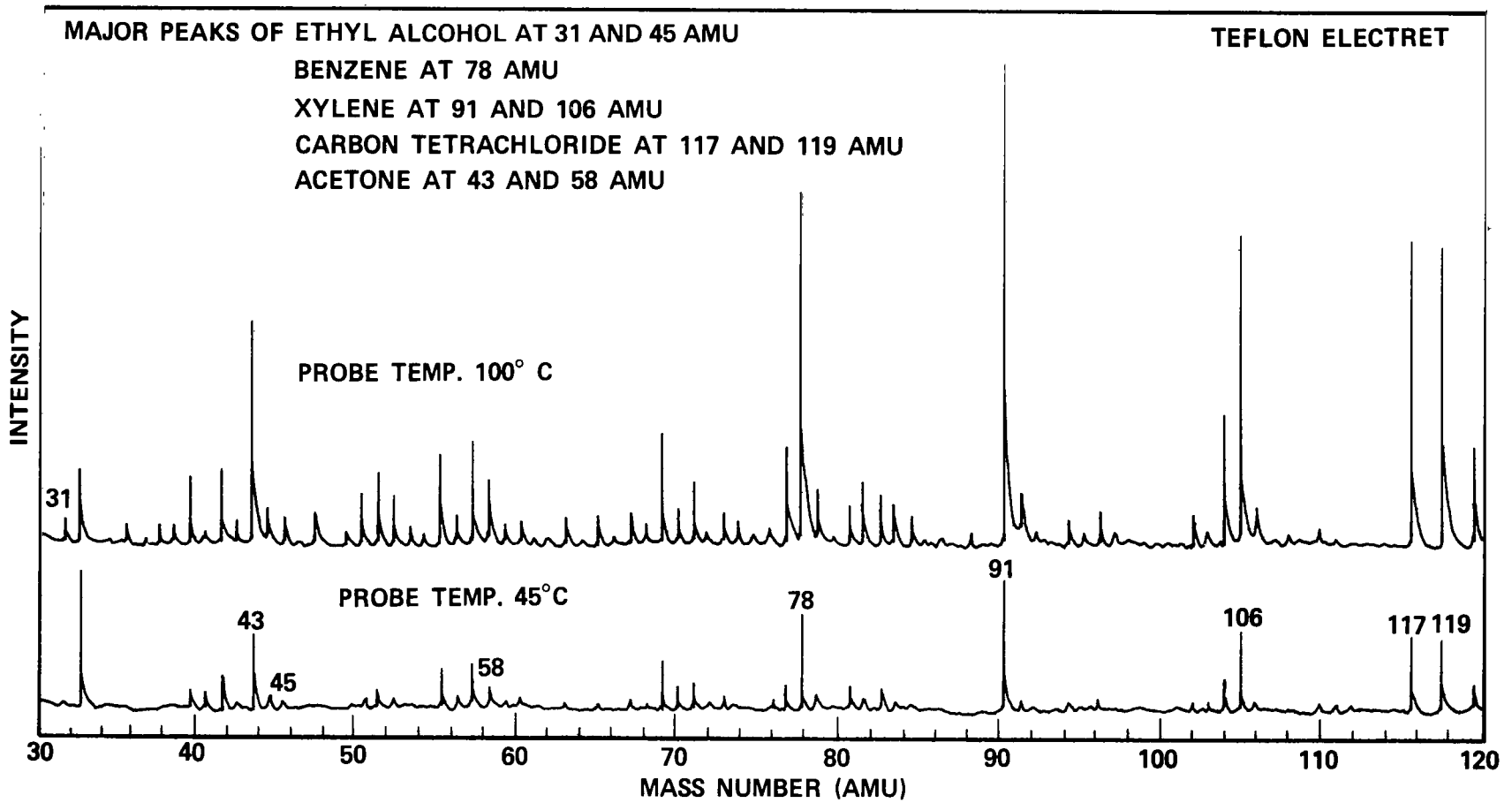


Figure 59. Major peaks from equal volumes of ethyl alcohol, benzene, xylene, carbon tetrachloride, and acetone from a Teflon electret exposed to vapors of these liquids.

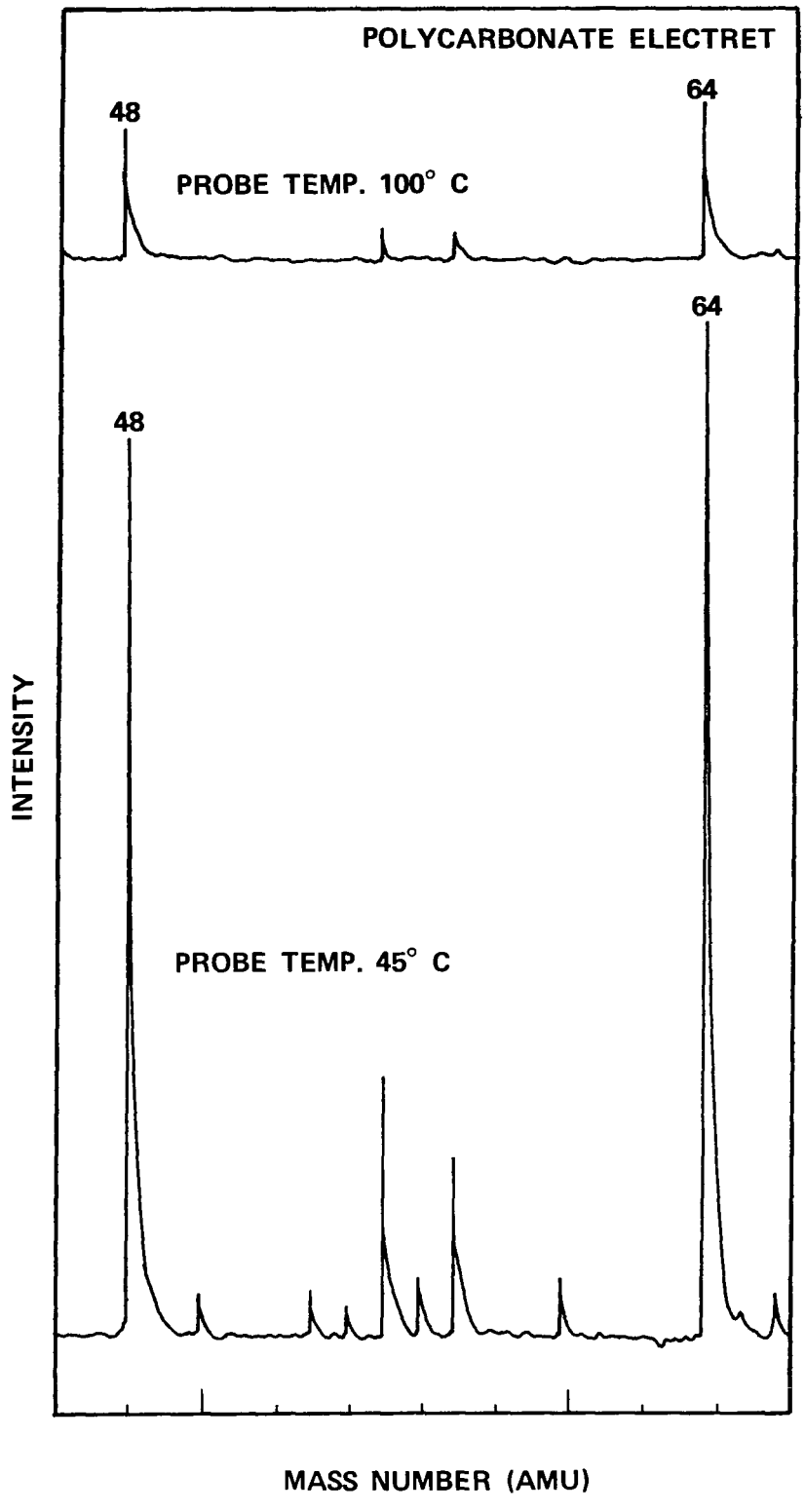


Figure 60. Major peaks of SO_2 from a polycarbonate electret exposed to SO_2 gas.

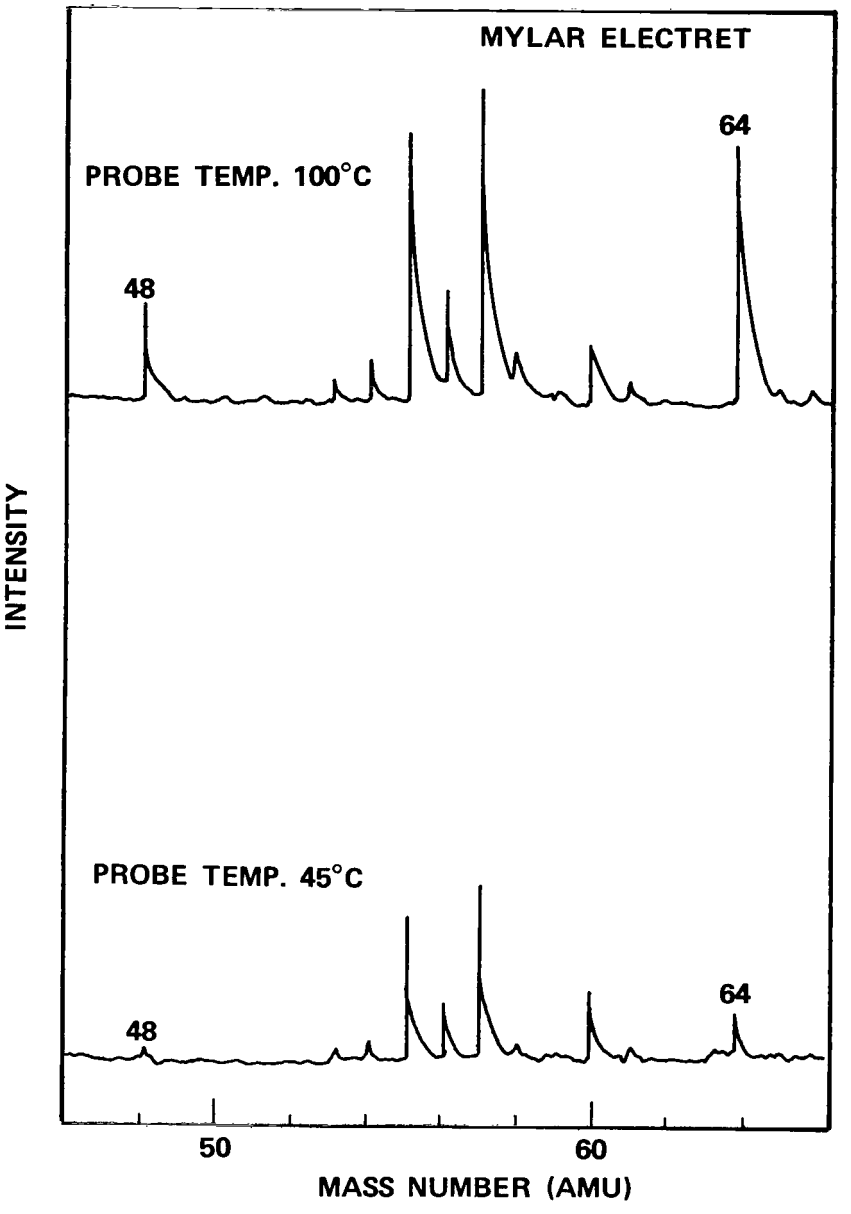


Figure 61. Major peaks of SO_2 from a Mylar electret exposed to SO_2 gas.

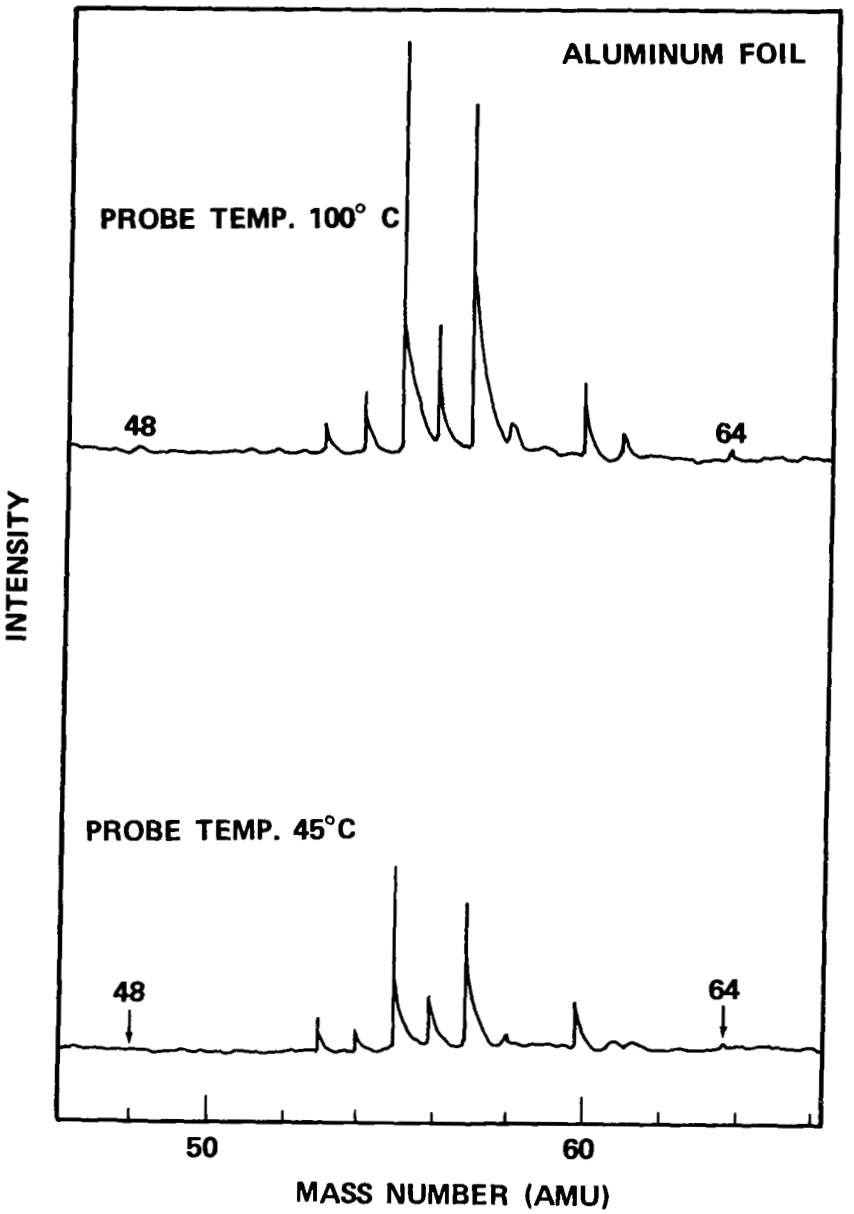


Figure 62. Major peaks of SO_2 from aluminum foil used as a control and exposed to SO_2 gas.

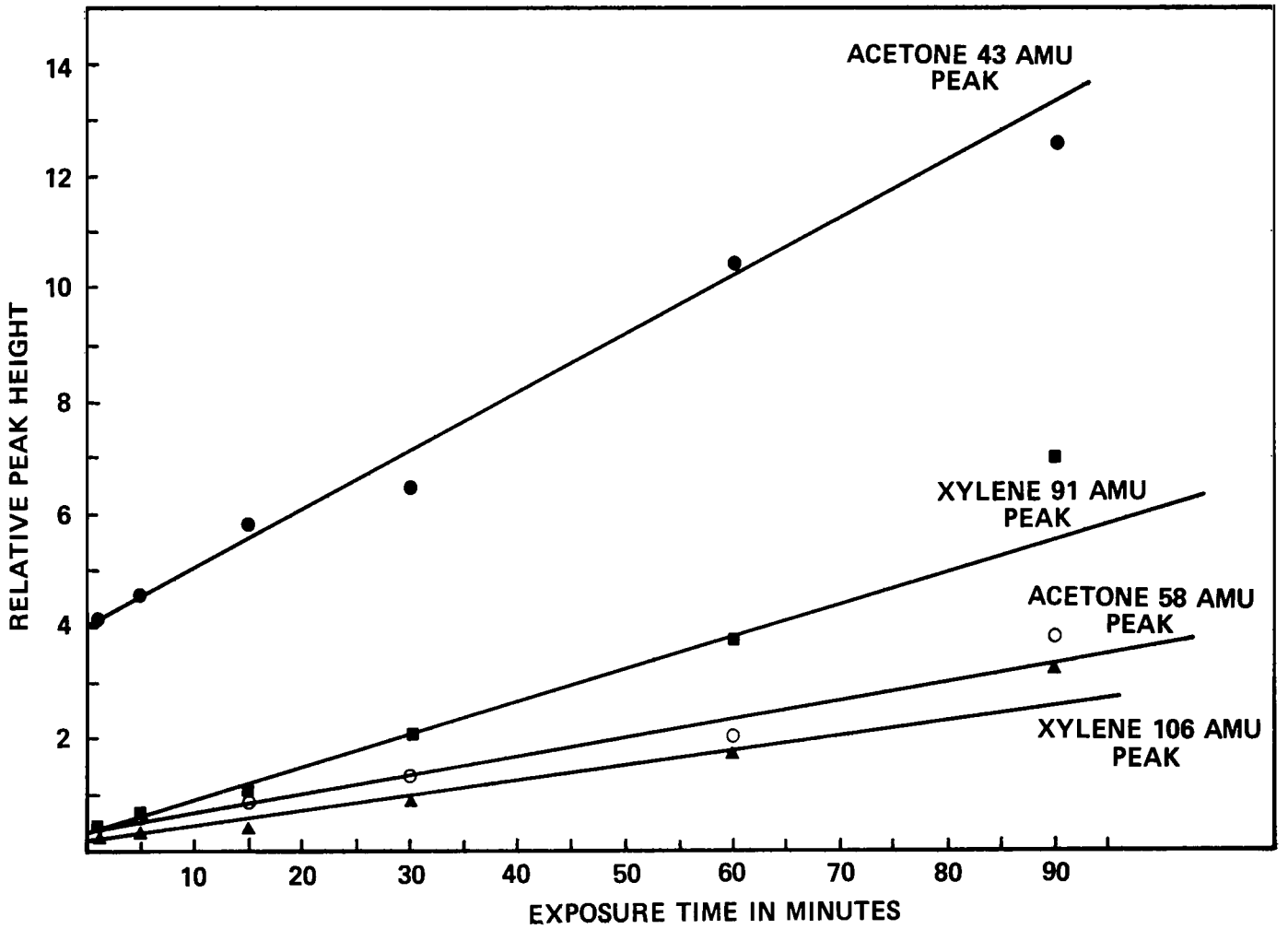


Figure 63. Teflon electret exposed to acetone and xylene exhibits a constant adhesive capability over the period of the test.

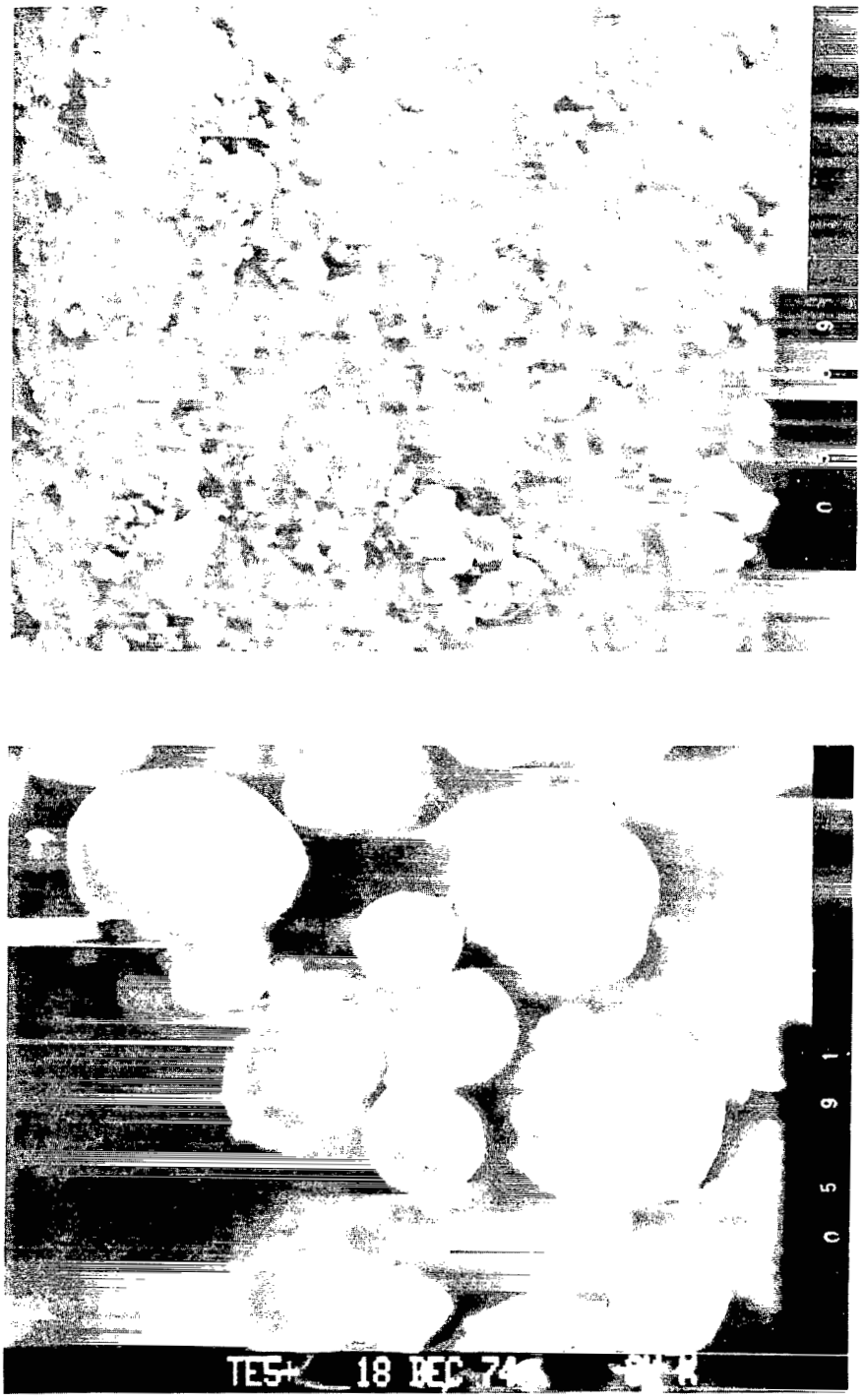


Figure 64. SCM photograph of Teflon electret surface that was exposed to rocket exhaust effluents.

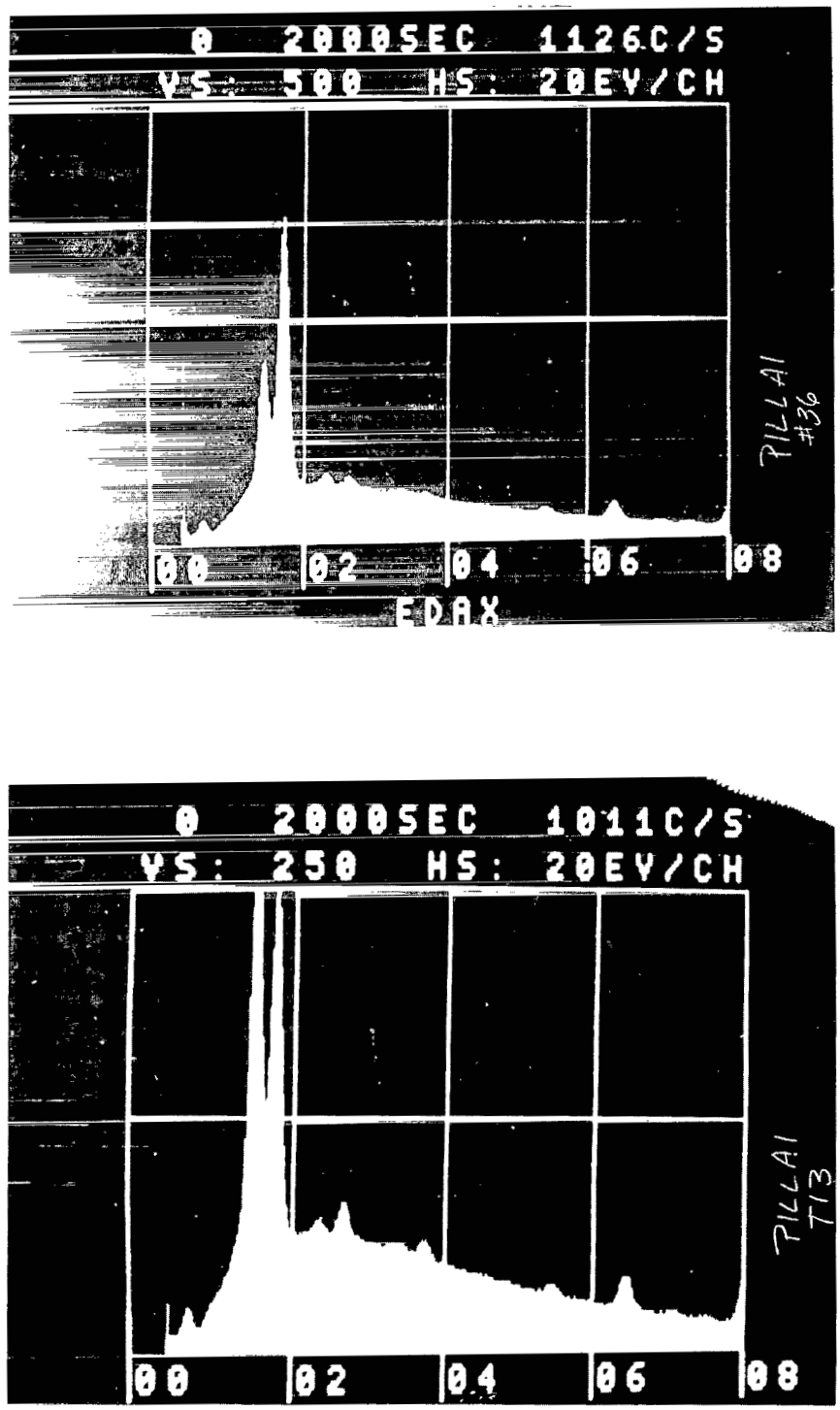


Figure 65. X-ray microprobe intensity spectra of the various rocket exhaust effluents collected on Teflon electrets.

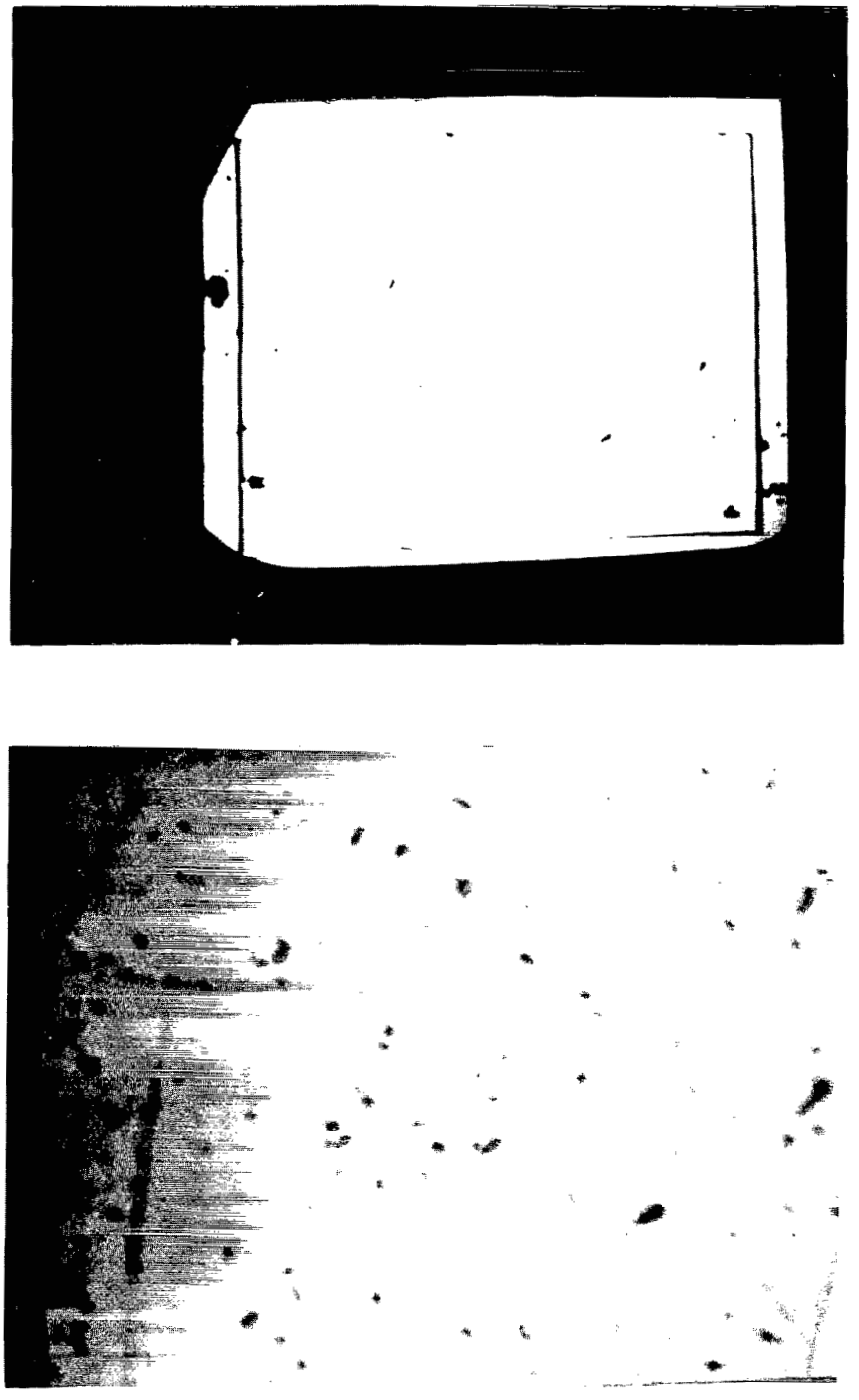


Figure 66. Electret surfaces with dust particles.

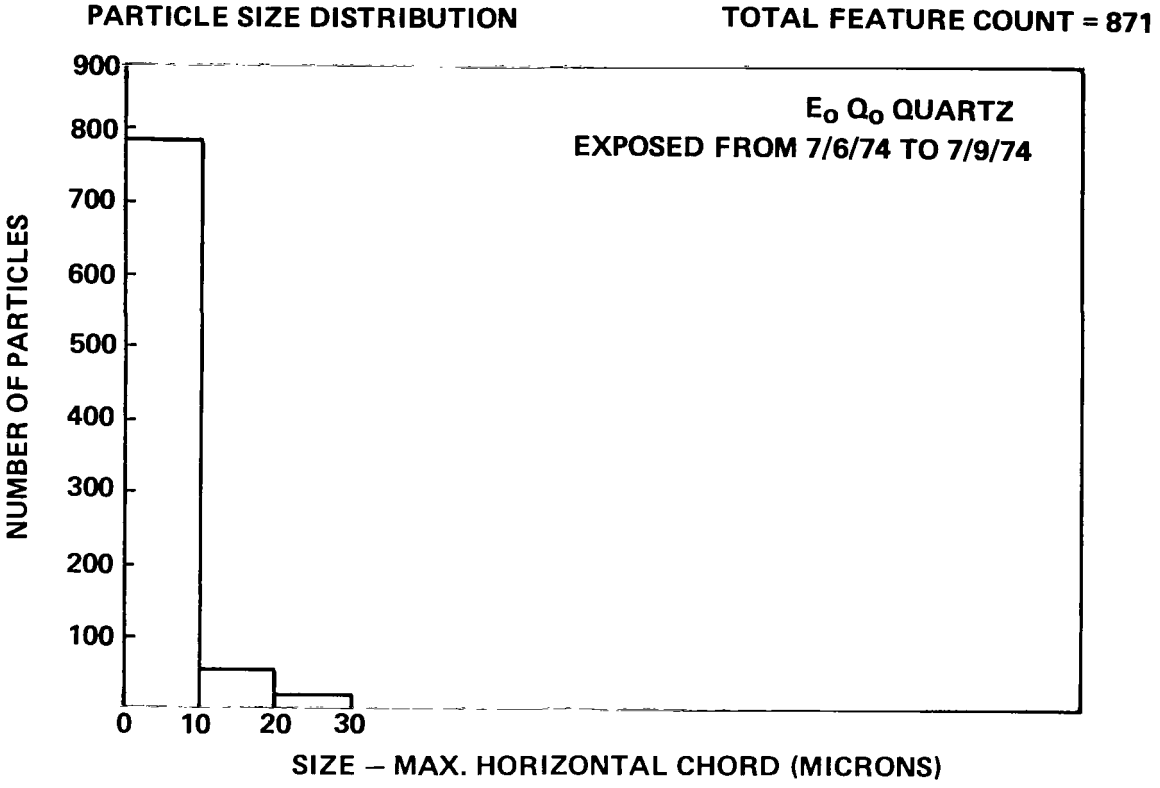


Figure 67. Particle collection properties of electrets. A fused quartz disc when exposed to the laboratory atmosphere in a cylinder of 25.4 cm (10 in.) diameter and 11.4 cm (4.5 in.) height without any electret lining for 3 days collected 871 particles of the distribution shown in the graph.

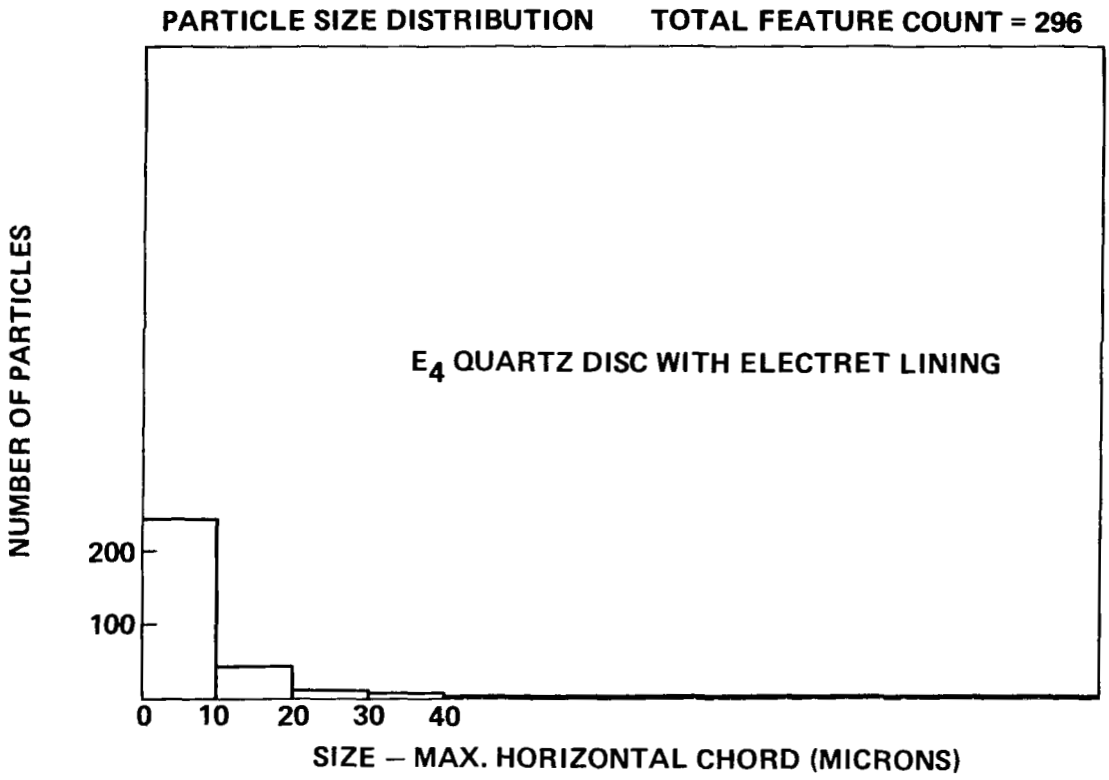


Figure 68. Particle collection properties of electrets. A fused quartz disc when exposed to the laboratory atmosphere in a cylinder of 25.4 cm (10 in.) diameter and 11.4 cm (4.5 in.) height with polymer electret lining for 3 days collected only 296 particles of the distribution shown in the graph.

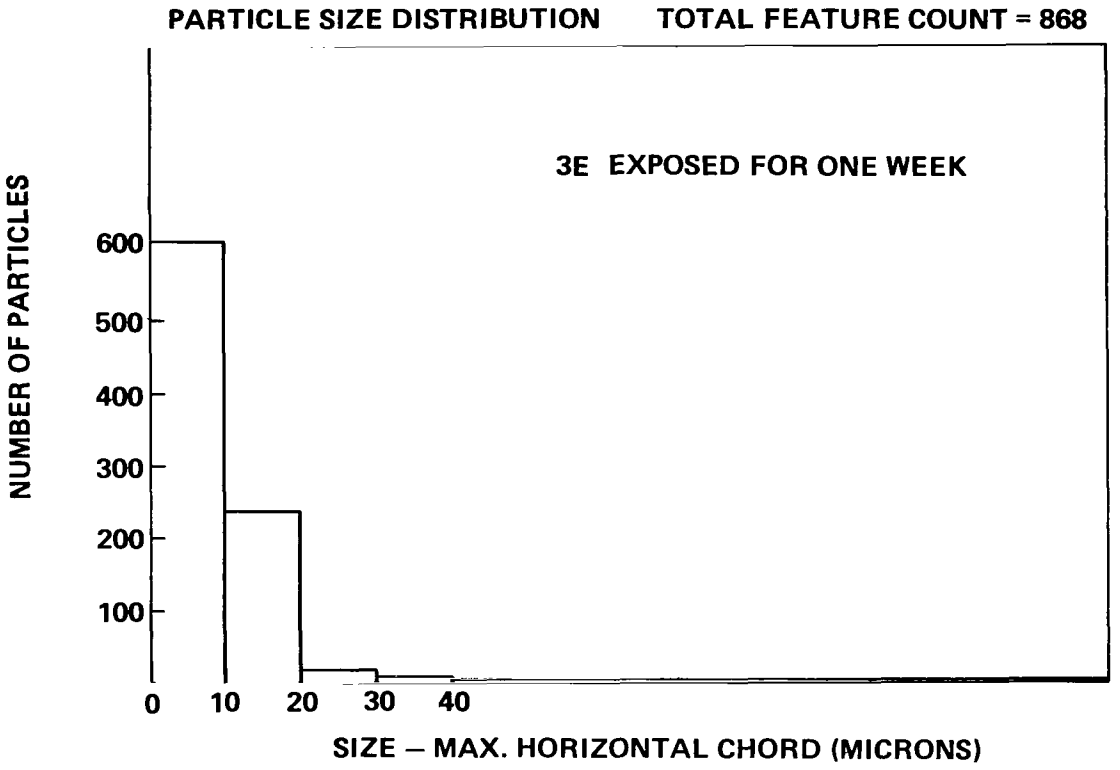


Figure 69. Particle collection properties of electrets. A quartz disc when exposed in a flow chamber cylinder [8.9 cm (3.5 in.) height and 7.6 cm (3 in.) diameter] without electret lining for 3 days collected 868 particles of the distribution shown in the graph.

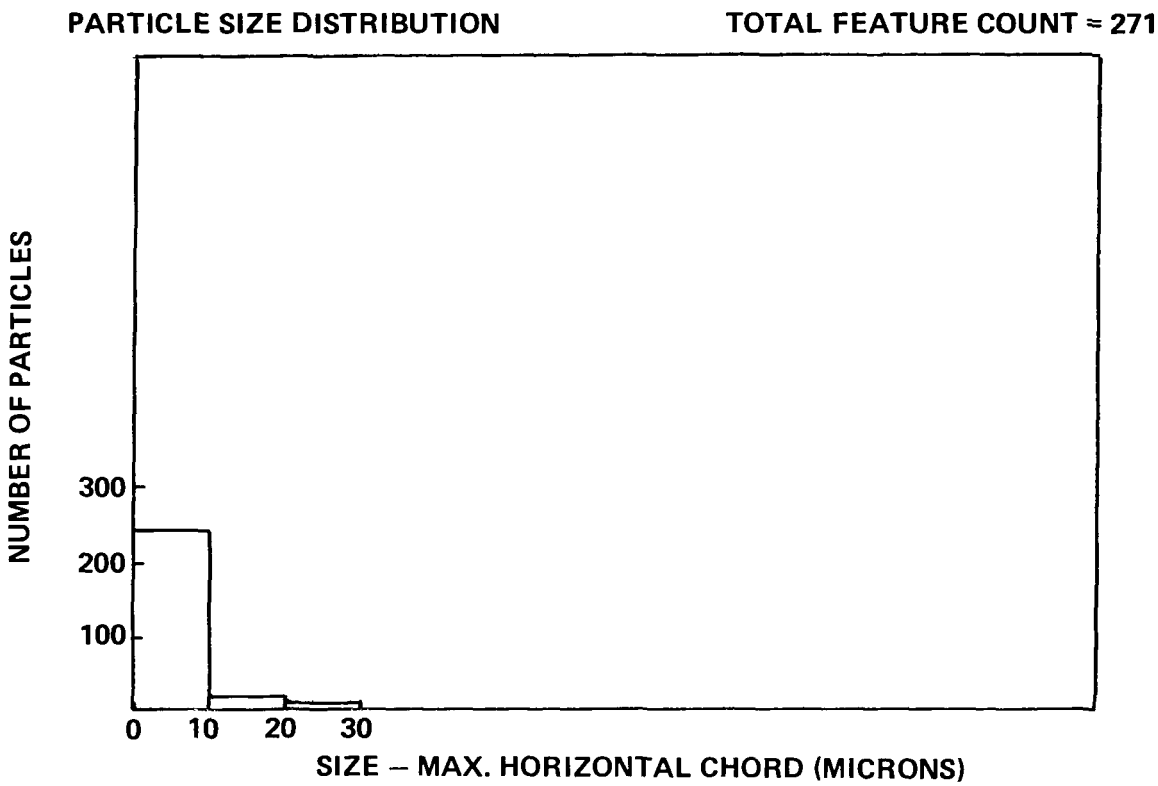


Figure 70. Particle collection properties of electrets. A quartz disc of 2.54 cm (1 in.) diameter when exposed to a flow chamber cylinder [8.9 cm (3.5 in.) height and 7.6 cm (3 in.) diameter] with electret lining collected 271 particles of the size distribution shown in the graph.

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Pillai, P. K. C. and Shriver, E. L.: Paper no. 56, Proceedings of the 147th meeting of the Electro-Chemical Society, held at Toronto, Canada, May 11-16, 1975.

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