The mass flow in the free molecule flow regime is governed by the Knudsen equation which, when rearranged, gives the average velocity as follows:

$$\bar{v}_x = -(4/3)(y_0/P)v_a(\partial P/\partial x) \tag{A8}$$

The constants in Eq. (A7) and (A8) agree if

$$\frac{4}{3} = [(2-f)/f](\pi/4), \quad \text{or} \quad f \sim 0.75 \tag{A9}$$

This value of f is somewhat lower than would be expected from experiment. By setting f equal to this value in Eq. A6 the following expression for $\bar{v}_x$ is obtained.

$$\bar{v}_x = (-y_0{}^2/3\mu)[1 + (4\mu v_a/P y_0)](\partial P/\partial x) \tag{A10}$$

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Dielectric Breakdown in a Dilute Plasma

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Introduction

RECENTLY, solar cell arrays operating at voltages up to 16 kv have been proposed as power sources in space. Array voltages in this range would be used to operate specialized electronic equipment without the need of a heavy power conditioning system. In 1968 R. K. Cole et al.[1] demonstrated the need for insulating such high voltage solar arrays from the electrically active plasma of the space environment at 500 km altitude. However, the effects of high voltage on desirable or candidate dielectrics are not well known and virtually no information is available on their breakdown voltages between a plasma and a metal electrode. Therefore, tests were made to determine these effects on the dielectrics now being considered for this application. The tests were performed at positive bias voltages as high as 20 kv d.c. relative to ground in an argon plasma with electron number densities of approximately 10^6 particles per cm^3.

Apparatus and Procedure

Facility

The tests were performed in a 0.46 m diam by 0.76 m long Pyrex bell jar mounted in a side port of a 3.05 m diam by 4.57 m long vacuum tank (Fig. 1). The tank was operated at a vacuum condition of approximately 2×10^{-5} torr. The test specimens were mounted on one end of a 3.2 cm diam cylindrical Pyrex sting. The ammeter used to detect dielectric breakdown and any leakage current preceding breakdown was located between the high voltage power supply and the test specimen. The wire connecting the test specimen, ammeter, and the power supply was shielded, with the shield at the potential of the test specimen. A 15-cm Kaufman ion thruster was used to generate the argon test plasma.

Test Specimens

The dielectrics tested are presented in Table 1. They are arranged in groups indicating their function in the design of a solar cell array (Fig. 2). Each specimen was positioned on the sting as shown in Fig. 3.

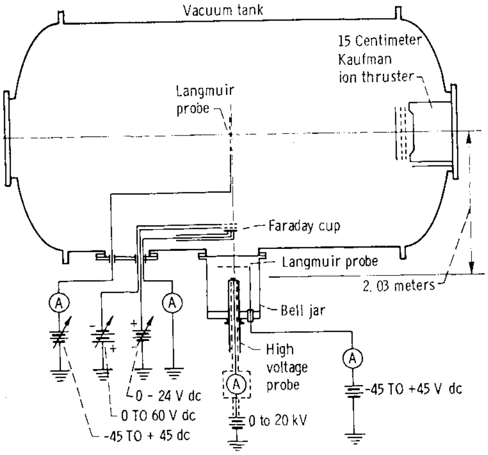

Fig. 1 Sketch of experimental facility (not to scale).

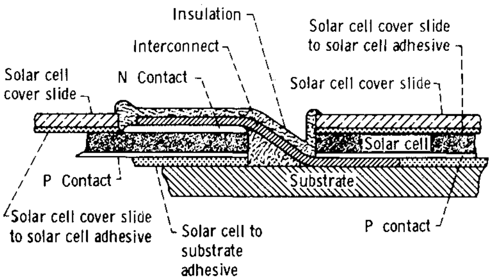

Fig. 2 Cross-sectional view of insulated solar cell assembly showing dielectrics.

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Table 1 Dielectric specimens test results

Specimen	Thickness in./cm	Dielectric breakdown, voltage, v	Plasma number density, pt/cm^3
Solar cell substrate materials			
Kapton H polymide film	0.0025	6,400	10^6
	0.0051	9,000	10^6
	0.0076	>20,000	6×10^5
	0.0127	>20,000	10^6
Teflon FEP			
Type A	0.0051	14,000	10^5
	0.0127	20,000	10^6
Type C	0.0127	>20,000	10^5
Type 20C	0.0051	17,000	10^5
	0.0051	>20,000	10^6
	0.0051	>20,000	3×10^5
	0.0051	>20,000	6×10^5
Teflon TFE	0.0127	>20,000	10^6
	0.025	>20,000	4×10^5
	0.055	>20,000	2×10^5
Nomex	0.0076	8,400	10^6
	0.0076	9,000	10^6
	0.0076	8,500	2×10^6
	0.0127	11,000	10^6
Mylar A	0.0076	>20,000	10^6
	0.0127	20,000	10^6
	0.025	>20,000	10^6
Solar cell to substrate adhesive			
RTV 511	0.0063	2,500	2×10^6
Rubber	0.030	>20,000	2×10^6
	0.051	>20,000	2×10^6
Solar cell cover to solar cell adhesive			
Sylgard	0.048	17,000	8×10^5
Type 182	0.066	>20,000	10^6
Solar cell cover slides			
Quartz 7940 Corning Glass	0.0076	>20,000	10^6
Insulation			
Parylene C	0.0025	12,000	2×10^6
(Union Carbide)	0.0051	>20,000	2×10^6
Parylene N	0.0025	12,500	10^6
(Union Carbide)	0.0025	14,700	10^6
	0.0051	16,100	2×10^6

Plasma Diagnostics

Ions enter the bell jar from the ion thruster beam as a result of scattering collisions. The most probable process is charge exchange collisions with the neutral background gas. This process produces slow ions that can enter the bell jar. The velocity and number density of the ions in the bell jar were estimated using two cylindrical tungsten Langmuir probes and a Faraday cup.

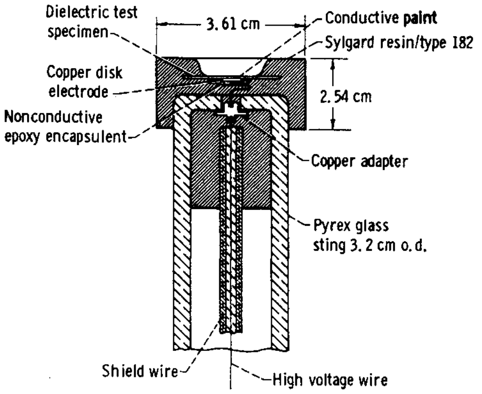

Fig. 3 Cross-sectional view of dielectric specimen mounted on end of high voltage Pyrex glass sting.

Number density: The plasma number density in the bell jar was found by two independent means. The first method uses the Langmuir probe in the bell jar. For the expected electron densities in the bell jar and beam, the Debye length is greater than the probe diameter, therefore, a thick sheath is expected about the Langmuir probe. The number density was determined according to electric probe theory^2 by

$$n^2 = (\pi^2/2A^2e^2)(m/e)S \tag{1}$$

where S is the slope of the square of the current vs the applied bias voltage in the electron saturation region, A the probe area, m the electron mass, and e the electronic charge.

The second method uses the current measured with the Faraday cup I_F and was calculated from the relation

$$n = I_F/(eAv) \tag{2}$$

where A is the area of the Faraday cup, e the electronic charge, and v is the velocity of the ions. The ion velocity was determined from a straightforward equating of the ion energy to the potential drop between the ion beam centerline and the location of the specimen using standard Langmuir probe techniques as described in Ref. 2. The values found using these two methods agree within a factor of three.

Experimental Procedure

After preparing a specimen and positioning it in the bell jar, the jar was evacuated to approximately 2×10^{-5} torr and allowed to outgas at this condition for at least 30 min before the high voltage test was begun. Voltage was applied in steps of approximately 500–1000 v and held constant for approximately 30 sec. This procedure was repeated until a limit of 20 kv was reached. The value of leakage current was recorded at each voltage step. If breakdown did not occur at the voltage limit of 20 kv, six 20 kv pulses of approximately 30-sec duration were applied to the test specimen to determine whether the dielectric would break down under a rapidly increasing electric field.

Results and Discussion

All test results were obtained with the specimen at room temperature and are shown in Table 1. Shown are the dielectric breakdown voltage and the argon plasma number density. The term dielectric breakdown voltage is defined here as that voltage which exerts sufficient electrical stress across a dielectric to completely destroy a section of it.

During the step application of the voltage, only the Kapton H polymide film, Parylene C and N, and RTV 511 rubber specimens showed increasing leakage current with increasing voltage. The variation with voltage of these currents preceding breakdown is shown in Figs. 4a–4c.

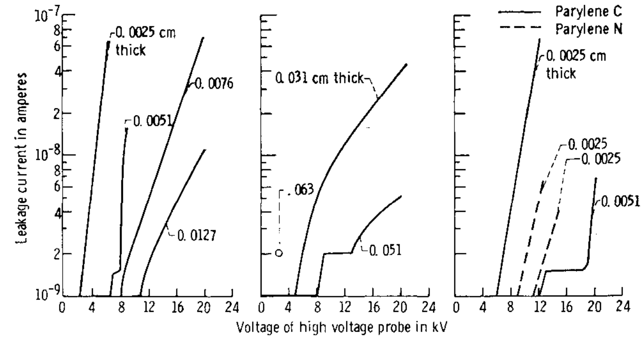

Fig. 4 Leakage current vs voltage through a) Kampton H polymide film, b) RTV 511 rubber, and c) Parylene C and N.

The dielectric breakdown voltage of the specimens (Table 1) ranges from a factor of one to four times larger than those presented in the literature (Ref. 3) where two metal electrodes were used. This difference may be explained by the following considerations. By making the plasma one of the electrodes, the total voltage drop occurs across the dielectric and some portion of the plasma. Therefore, a larger voltage is required to reach the breakdown strength of the dielectric. Another possible explanation comes from considering the effect of the electric field at the dielectric surface when a metal electrode is placed in contact with it. Asperities of the metal surface can cause the electric field to vary widely over the surface. Therefore, the dielectric adjacent to it may be more susceptible to breakdown than if the metal electrode is replaced with a plasma.

In increasing the applied voltage until breakdown occurred or until the maximum of 20 kv was reached during a test, it was noticed that some specimens displayed randomly recurrent instantaneous surges of leakage current (on the order of microamps) during otherwise steady-state conditions. The specimens that showed surges of leakage current were Kapton H polymide film, Teflon TFE, Teflon FEP, Mylar A, Quartz 7940 Corning glass and Parylene C and N. No tests were run to determine the threshold voltages for the beginning of these current surges.

The 20 kv pulses did not break down any of the specimens which had not broken down during the 20 kv limiting voltage tests. This indicates that the rapidly increasing electric field had no measurable effect on the breakdown voltage of the dielectric up to these values. The holes after breakdown were irregular in shape and varied in area up to approximately 0.0048 cm^2.

The plasma number densities were calculated using Eq. (1) and the experimental saturation electron current of the Langmuir probe in the bell jar. The electron temperature determined from the I-V characteristic of the Langmuir probe in the bell jar was approximately 3000 K ($\simeq$0.3 ev). The plasma velocity was on the order of 2.4 km/sec which is about one third the satellite velocity for a 300 km altitude orbit.

Conclusions

Within the solar cell substrate group of materials tested the Teflon FEP specimens displayed higher breakdown voltages than did the Kapton H polymide film, Nomex, and Mylar A specimens. The Teflon TFE specimens of this group are excluded from this comparison because at the thickness tested they did not break down below or at the 20 kv limiting test voltage. Further, approximately equal values of breakdown voltage were observed for the 0.0051 cm thick specimens of Teflon FEP and those of the insulation group Parylene C and N. However, leakage currents were observed through the Parylene C and N specimens with none observed through the Teflon FEP specimens.

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