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Dielectric Strength of Rigid Urethane Foam

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Acknowledgment

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Abstract

Cellular plastics are being considered as lightweight encapsulants for electronic packaging in space applications. This study was carried out to assess the importance of the various parameters pertaining to the electrical properties of foams and, thus, provide a basis for the prediction of the life-time of foam-packages operating in space environment. This report deals mainly with the dielectric breakdown foam structure relationships. It was found that the dielectric strength of a foam will be improved by the following characteristics: (1) uniform cells and minimum void content, (2) small and symmetric cells, (3) gas pressure and type of gas (fluorocarbons), (4) thick and stress-free window, and (5) density (between 6 and 10 lb/ft^3).

Dielectric Strength of Rigid Urethane Foam

I. Introduction

Cellular plastics are attractive as dielectric materials for space applications because of their low dielectric constant and loss factor, low weight-to-strength ratio, RF transparency, and impact protection. For future space missions there is need for components that will operate reliably over periods of up to several years in the rigor of the space environment.

A survey of the literature disclosed that very little meaningful information is available on the various parameters pertaining to the electrical properties of foams. This lack of information dictated the exclusion of foams from the Jet Propulsion Laboratory specifications for high-voltage packaging (Ref. 1), and created the need for a systematic and comprehensive study. Although motivated mainly by spacecraft problems, the work was forced by necessity to take a broader approach.

For high-voltage space applications, conditions conducive to electric failure occur when operating at reduced pressure, i.e., when the gas pressure is in the *critical region* in which the gas will support corona or arcing. Such conditions exist in terms of earth altitude between 60,000 and 310,000 ft. It is believed that the failure of the

TV cameras on *Mariner IV* was due to arcing caused by an accidental power turn-on during ascent through the upper atmosphere. Corona problems are encountered with antennas of high-flying airplanes. For the *Voyager* lander, an antenna will have to be encapsulated for impact protection and for operation in the low atmospheric pressure on the surface of Mars (10 to 50 torr; Ref. 2). In deep space, i.e., vacuum of less than 10^{-5} torr, occurrence of gas supported discharge is not possible, but problems can be caused by inadequately ventilated areas, such as voids around connectors (Ref. 3).

The relationship of the breakdown voltage and the product of the pressure P times the separation δ between two parallel plates (Fig. 1) is given by Paschen's Law which was discovered experimentally in 1889. For any given $P\ \delta$ product, a breakdown voltage exists with an arc occurring. Part A of Fig. 1 shows that Paschen's minimum occurs at about 330 V, indicating that any voltage under 330 V will not arc over regardless of air pressure or geometry. The breakdown of solid dielectrics is caused quite commonly by discharges in gases within flaws or voids, but other mechanisms are possible, as discussed later. Although a foamed plastic can be viewed as a composite of a polymer and a gas, the breakdown behavior cannot be predicted by interpolating between solid and gas behavior.
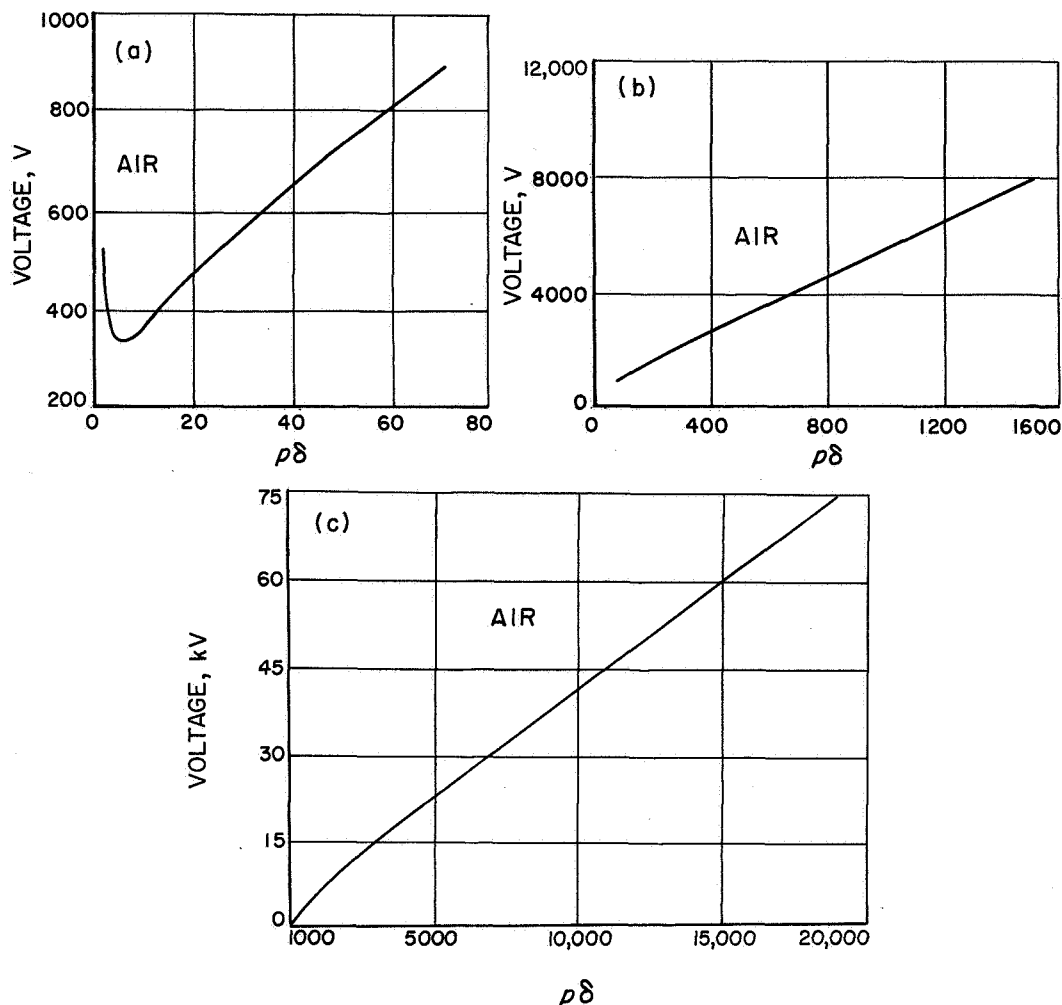
Fig. 1. Arcing voltage versus product of pressure and separation of parallel plate (Paschen's Law)

The purpose of this paper is to discuss the effect of the following parameters on the electrical properties of cellular plastics: (1) chemical composition of both gas and polymer, (2) density, and (3) cell size, structure, and orientation. The main emphasis is on the dielectric breakdown, which is the principal area of our work to date, but some aspects of dielectric properties and corona are also included. A detailed analysis of gas diffusion in a closed-cell foam was presented in the literature (Refs. 4 and 5).

II. Test Methods

Dielectric strength or electric breakdown of plastics is defined as the point at which voltage can no longer be maintained across the material without excessive flow of current or the physical disruption of the material. Several types of electric breakdown can be recognized in solids: intrinsic breakdown, physical-defect-dependent breakdown, thermal breakdown, and discharge-dependent breakdown. It is important to recognize the existence of the different types of breakdown, since different conditions and material characteristics may emphasize different modes of failure (Ref. 6). But for cellular materials, the discharge-dependent breakdown is without much doubt the major cause of breakdown.

The voltage stress gradient E across a uniform sample is defined by:

$$E = V/t$$

where V is the voltage, and t is the specimen thickness. The voltage gradient at failure is defined as breakdown

stress, breakdown strength, electric strength, or dielectric strength. A flashover is a failure that may occur around the edges instead of through the volume of the sample. In general, flashover is not considered a property of the material.

A detailed description of experimental requirements and specifications of test conditions is given in ASTM D149-61 *Standard Methods of Test for Dielectric Breakdown Voltage and Dielectric Strength of Electrical Insulating Materials at Commercial Power Frequencies.* These test methods cover procedures for testing solid, semisolid, and liquid electrical insulating materials. The tests are also applicable to cellular plastics.

For this study, measurements were made with a Dielectric Strength Test Set Model PDA-1 (Industrial Instruments Inc.), using the 60-cycle mode. This tester meets the ASTM specifications. Figure 2 shows a foam specimen in the test compartment. Cylindrical brass electrodes
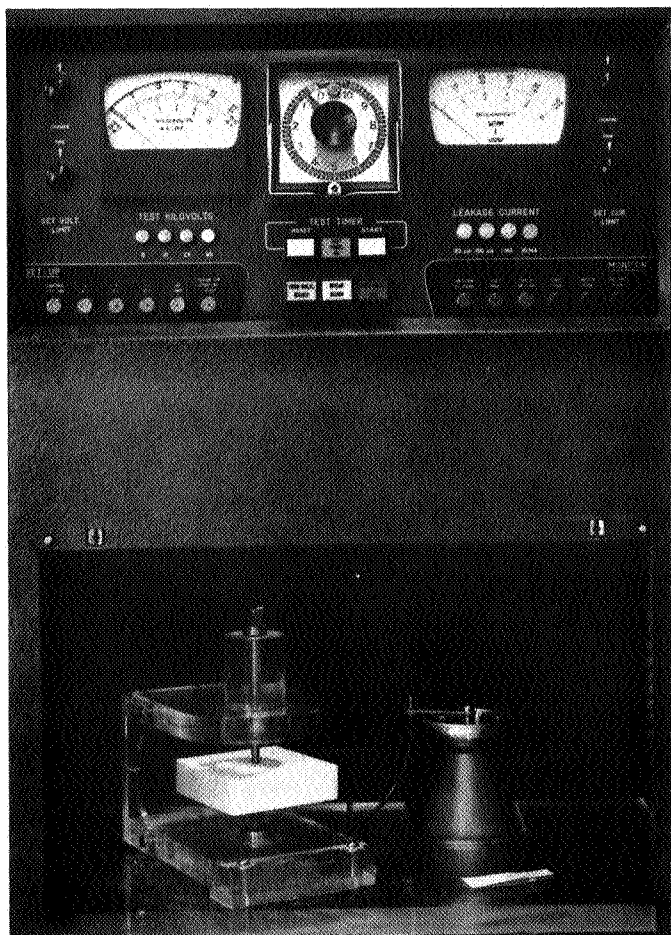

Fig. 2. Dielectric Strength Test Set Model PDA-1

(¼ in.) with rounded edges were used. To ascertain the stability of the tester, the breakdown voltage of air was checked periodically; the breakdown voltage for a 1-in. air gap was 17 ±1 kV. The foam specimen size was at least 4 × 4 in. to avoid flashover. The thickness varied between 0.25 and 1.00 in.; the optimum value was dictated by the 50-kV$_{rms}$ limit of the instrument.

III. Experiments and Results

Experiments were conducted on the following urethane foams to determine the effect of various parameters on the electrical properties: rigid water-blown foam, flexible water-blown foam, and rigid fluorocarbon-blown foam.

A. Water-Blown Rigid Foam

The initial phase of this study was carried out on Eccofoam S and SH (Emerson and Cuming, Inc.) water-blown, rigid, closed-cell urethane foams, distributed as 1-in.-thick sheet stock. These foams are available in densities between 2 and 26 lb/ft^3. According to the manufacturer, Eccofoam S can be used between −70 and 150°C without physical deterioration and Eccofoam SH, a high-temperature foam, between −70 and 204°C. Tests were carried out on specimens as received.

1. Effect of density and blowing gas pressure. For each density, five breakdown tests were made, and the length of the vertical line (Fig. 3) indicates the spread of the data points. For the 2-lb/ft^3 specimen, however, 25 tests were made with no apparent increase in the spread of data points, indicating that 5 tests yielded a reasonable estimate of the statistical deviation for this test procedure. Some specimens were outgassed at 80°C in a vacuum of 1 torr before breakdown testing. In this context outgassing is the outward permeation of volatile components from a foam placed in vacuum. The specimens were allowed to cool to ambient temperature under vacuum to minimize back diffusion of gases into the foam (Refs. 4 and 5). The actual core density of the test specimens was determined by weighing a 2-in. cube.

Inspection of Fig. 3 shows that the breakdown strength E_b for the 2-lb/ft^3 foam is 25 kV/in. as compared to 17 kV/in. for air at 1 atm. This increases further to about 38 kV/in. for the 8-lb/ft^3 specimen. For specimens outgassed for 6 days, a reduction of about 8 kV/in. is observed, and an additional loss of 5 kV/in. for those outgassed for 37 days.

The actual pressure of the blowing gas in outgassed specimens was not determined, but reasonable estimates
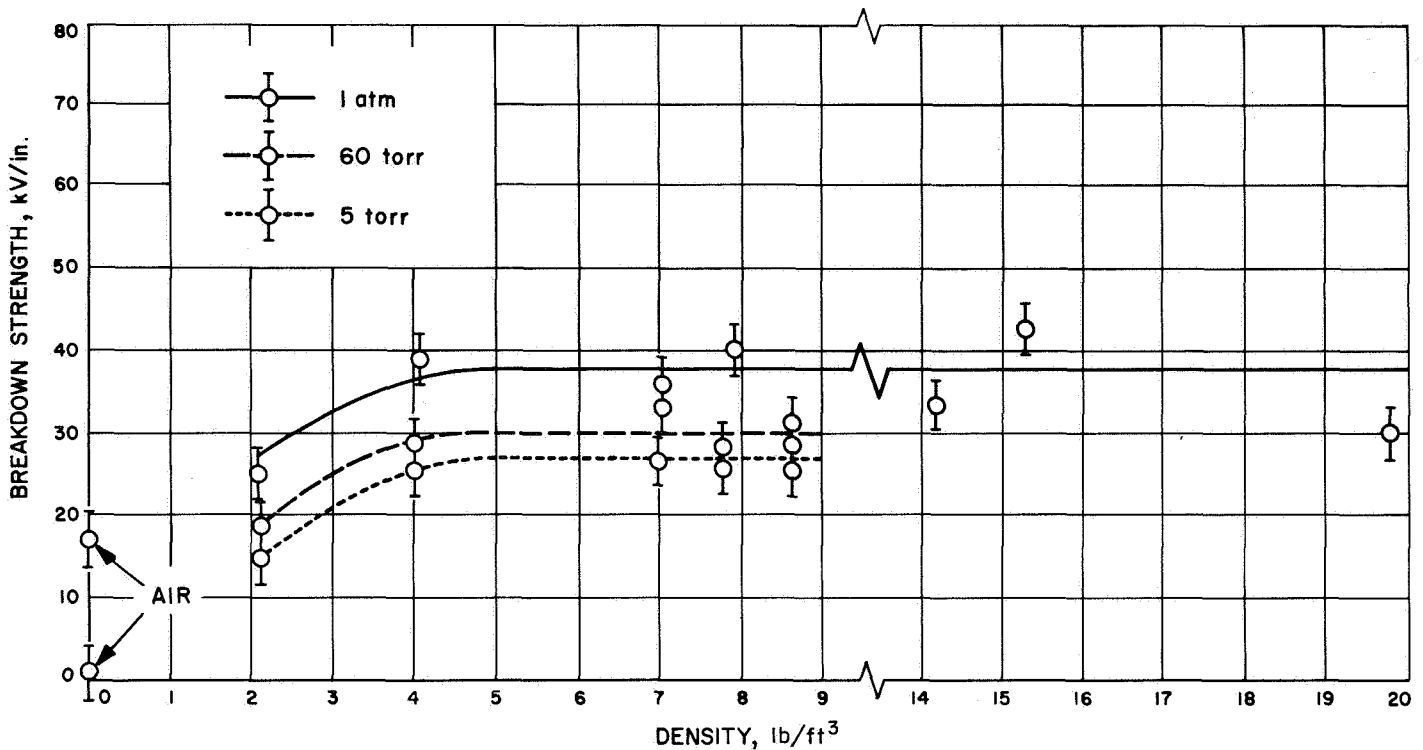
Fig. 3. Breakdown strength versus density for Eccofoam

may be made on the basis of previous studies on the out-gassing behavior of foams (Refs. 4 and 5). After 6 days at 80°C, the blowing gas loss should be expected to be approximately 90%, leaving the remaining gas at an average pressure of about 60 torr. After 37 days about 99% of the gas should be removed, and the pressure should be about 5 torr. Since only about 1% of the gas is left after 37 days, it appears that during this period the asymptotic value for the strength of the foam has been approached. For comparison, Fig. 4 shows the change of voltage with pressure for CO_2 and N_2.

2. Dependence of E_b on rate of voltage application. To assess the effect of the rate of voltage application on E_b, a series of tests was carried out on a 2-lb/ft³ Ecco-foam SH. By varying the rate, the time to breakdown τ could be increased from the usual 30 to 60 s for short time tests to 2 to 3 h. The results are shown in Fig. 5.

3. Dependence of E_b on thickness. For this study, sheets of 2.5- and 6.0-lb/ft³ Eccofoam SH were used. Thickness was varied from approximately 0.15 to 2.0 in.

The test results for both foam densities are shown in Fig. 6 as plots of log V_b versus log t, where V is the voltage at breakdown and l is the specimen thickness.

These plots yield good straight lines. The slopes for 2.5- and 6.0-lb/ft³ foams are about 0.6 and 0.5, respectively. These results show that, in this respect, a foam behaves like a solid. The slope for the 2.5-lb/ft³ foam is only slightly higher than 0.5, a value which is also characteristic of a solid. Since a density of 1.8-lb/ft³ is the practical lower limit for rigid urethane foams, the 0.5 value should represent the behavior of foams for all densities of interest.

B. Water-Blown Flexible Foam

Seven flexible foams were received from Scott Paper Company (through the courtesy of Dr. E. A. Blair). The cell size varied by a factor of ten; the content of broken cell windows was high in all samples. The averages of the 5-test results on the 2-lb/ft³ foams are tabulated in Table 1.

C. Fluorocarbon-Blown Rigid Foam

All the fluorocarbon-blown foams were prepared at Wayne State University, using a Martin-Sweets Company laboratory model foam machine. The foaming apparatus consisted of a three-component positive displacement metering and mixing machine with a maximum capacity of 2 lb/min. Core samples selected for testing were cut out from buns approximately 4 × 9 × 4 in.

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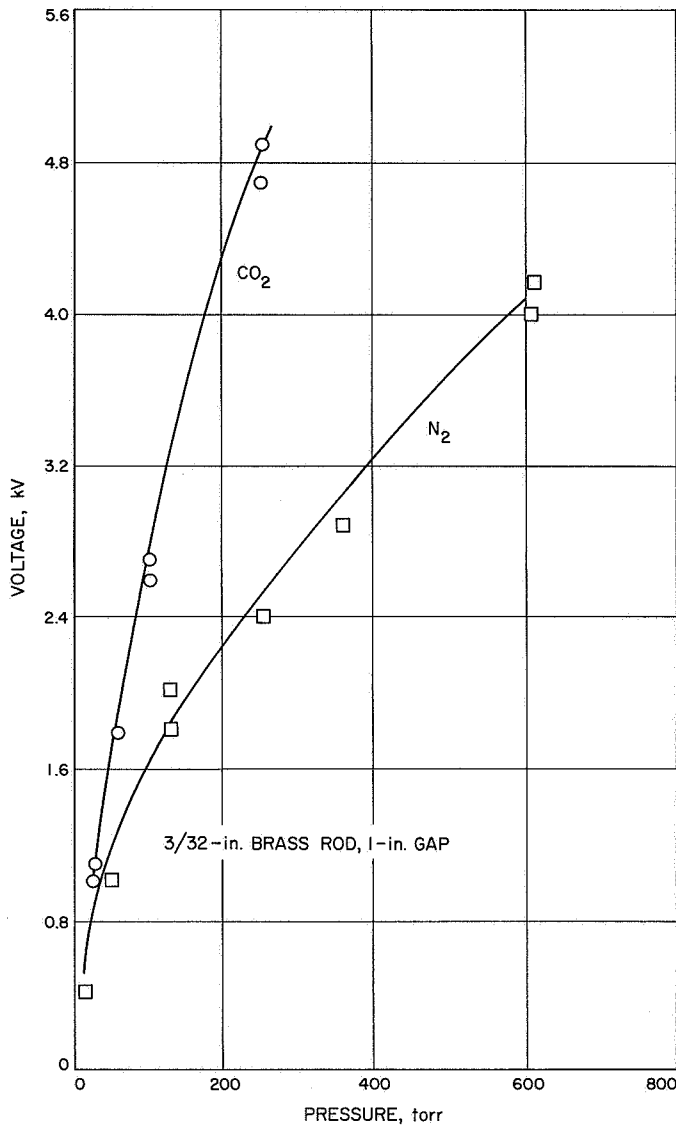
Fig. 4. Voltage at onset of corona vs pressure
for CO_2 and N_2

Table 1. Dielectric strength of flexible urethane foam

Number of cells/in.	Thickness, in.	E_b, kV/in.
10	0.41	36.5 ±1.2
20	0.45	33.3 ±0.0
30	0.44	35.4 ±1.2
45	0.51	32.8 ±1.2
60	0.46	32.3 ±1.2
80	0.50	30.5 ±0.5
100	0.45	34.7 ±1.0

1. Effect of polymer composition on breakdown. Series
of foams varying in composition have been prepared
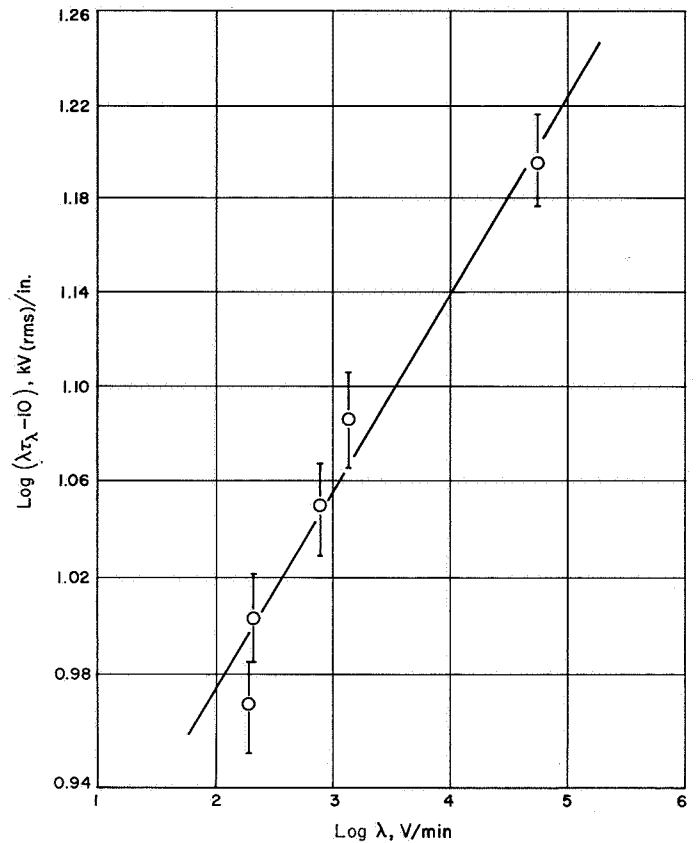
Fig. 5. Dependence of breakdown voltage on rate of
voltage application λ, according to Eq. (9)
(Eccofoam, 2 lb/ft^3)

(Table 2). These samples were tested without regard to
the direction of foam rise. Near the end of the measure-
ments, strong directional effects were discovered. For all
subsequent tests, the orientation of the test specimen was
recorded. Because of the neglect for directional effects,
the comparisons of these results in terms of the effect of
formulation on E_b are inconclusive; however, increasing
the crosslinking density in the polymer apparently in-
creases E_b (formulations 3057 and 3024). This problem
did not arise with Eccofoam specimens, which were fur-
nished as 1-in.-thick slabs, and thus, by necessity, were
tested only in the direction of foam rise.

2. Effect of density and cell size. Two representative
formulations were selected from Table 2: 3111-5 (low
crosslink) and 3024-17-35 (high crosslink). For each of
these, the fluorocarbon content was varied to change the
density. In addition, the longest dimension of the foam
cell was measured in each direction, i.e., with (||) and
across (⊥) the direction of foam rise. The diameter of
the strut was also recorded.

Item	Formulation						
	3079-10	3079-13	3079-17	3079-18	3079-32	3079-33	3079-34
Component, parts by weight							
Polyol A[a]	83.4	83.4	56.0	56.0	55.0	55.0	55.0
Polyol B[b]	—	—	—	—	—	—	—
Polyol C[c]	—	—	—	—	—	—	—
Polyol A-TDI prepolymer	100.0	100.0	100.0	100.0	83.0	83.0	83.0
PAPI	—	—	—	—	—	—	—
Freon R-11	28.0	40.0	22.0	28.0	27.0	21.0	33.0
Silicone oil SF-1079	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Silicone oil DC-201	—	—	—	—	—	—	—
Triethylenediamine	0.15	0.15	0.2	0.2	0.08	0.08	0.08
THANCAT DME[d]	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Dibutyltin dilaurate	—	—	—	—	—	—	—
Phosgard C-22R[e]	—	31.0	—	—	—	—	—
Fyrol 6[f]	—	—	31.0	31.0	—	—	—
Virol 82[g]	—	—	—	—	30.0	30.0	30.0
Bulk density, lb/ft^3	1.95	1.68	1.94	1.84	1.95	2.51	1.63
E_b, kV/in. (unknown orientation)	72.0 ± 10	63.6 ± 10	72.2 ± 6	88.0 ± 18	80.5 ± 6	84.0 ± 8	85.4 ± 12
Thickness, in.	0.45 ± 0.2	0.47 ± 0.15	0.46 ± 0.10	0.30 ± 0.10	0.46 ± 0.10	0.30 ± 0.68	0.48 ± 0.10
Number of tests	10	9	10	10	8	10	10
E_b, kV/in. ($\perp$ to foam rise)	—	—	—	—	—	—	—
Thickness, in.	—	—	—	—	—	—	—
Number of tests	—	—	—	—	—	—	—
E_b, kV/in. (‖ to foam rise)	—	—	—	—	—	—	—
Thickness, in.	—	—	—	—	—	—	—
Number of tests	—	—	—	—	—	—	—

[a] Propylene oxide adduct of sorbitol; molecular weight = 700.
[b] Propoxylated Mannich reaction product from phenol-diethanolamine-formaldehyde (molar ratio = 1:3:3); equivalent weight = 350.
[c] Same as b, but equivalent weight = 650.
[d] Jefferson Chemical Company.
[e] Monsanto Chemical Company.
[f] Victor Chemical Division, Stauffer Chemical Company.
[g] Mobil Chemical Company.

Table 2. Composition and properties of fluorocarbon blown urethane foams

Formulation								
3079-48	3079-30	3111-2	3111-3	3111-4	3111-5	3057-36-2	3024-17-35	3024-28-4
78.0	—	65.0	78.0	65.0	78.0	—	—	—
—	—	—	—	—	—	17.15	36.6	33.4
—	—	—	—	—	—	17.15	—	—
—	—	—	—	—	—	47.1	47.9	48.7
100.0	—	99.0	100.0	99.0	100.0	—	—	—
31.0	—	28.0	33.0	28.0	36.0	13.0	15.0	12.5
1.1	—	1.0	1.2	1.0	1.1	—	—	—
—	—	—	—	—	—	0.6	0.5	0.5
0.6	—	0.6	1.0	0.8	0.4	—	—	—
—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	0.03	0.006
13.2	—	—	30.0	—	—	—	—	—
—	—	13.0	—	13.0	—	5.0	—	4.9
—	—	—	—	—	—	—	—	—
2.11	—	2.08	2.18	2.03	1.72	1.95	1.75	2.08
93.9 ± 15	84.7 ± 5	96.0 ± 14	98.8 ± 12	93.9 ± 19	106.4 ± 9	158.6 ± 13	144.1 ± 17	133.6 ± 29
32 ± 0.01	0.46 ± 0.08	0.35 ± 0.02	0.35 ± 0.02	0.26 ± 0.06	0.32 ± 0.02	0.25 ± 0.02	0.18 ± 0.08	0.24 ± 0.04
5	10	5	4	6	7	6	9	9
—	—	—	—	—	—	153.5 ± 10	152.8 ± 2	146.7 ± 2
—	—	—	—	—	—	0.26 ± 0.01	0.24 ± 0.01	0.26 ± 0.01
—	—	—	—	—	—	3	2	2
109.4	—	—	—	—	—	106.9 ± 10	147.2 ± 2	98.8 ± 1
0.265	—	—	—	—	—	0.25 ± 0.02	0.26 ± 0.01	0.26 ± 0.00
1	—	—	—	—	—	3	2	2
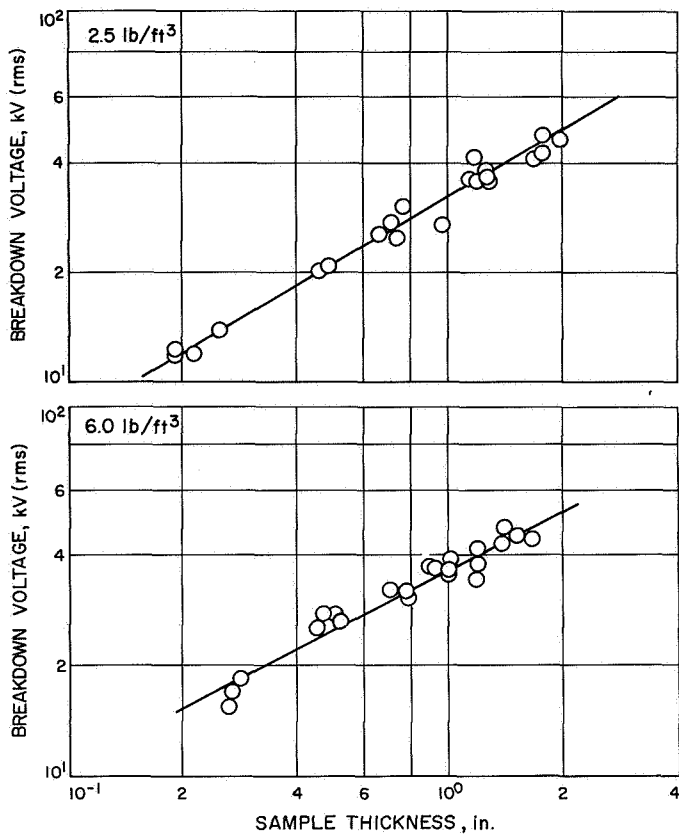
**Fig. 6. Dependence of breakdown voltage on sample thickness (Eccofoam)**

These measurements were made with a binocular microscope at 34× magnification (10× eyepiece and 3.4× objective). The eyepiece scale was calibrated with a reference slide (52 divisions = 1.0 mm).

Table 3 summarizes the results on formulations 3111-5 and 3024-17-35. These data demonstrate the strong correlation between E_b and the cell dimension in direction of the electric field.

Currently, JPL is carrying out a study on the correlation of cell structure with E_b. Figure 7 illustrates the variety of cells encountered. It is apparent that features such as the distribution of polymer between struts and windows, uniformity in cell size, and structural integrity of windows depend strongly on the formulation.

IV. Discussion

The following presents some aspects of the dielectric breakdown in solids, and discusses the breakdown in
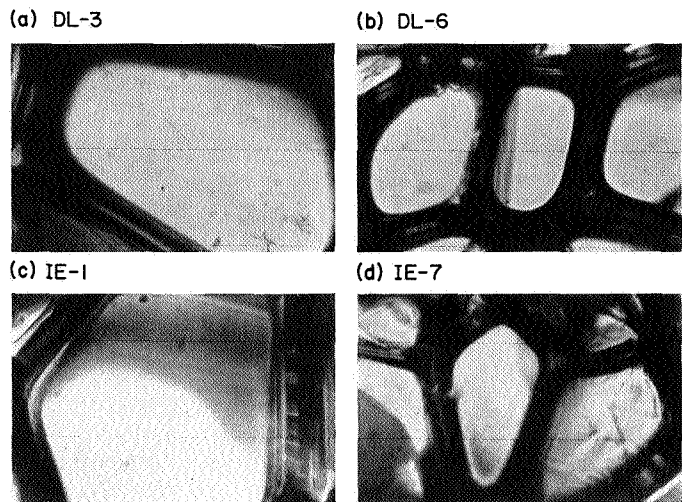
DL-3 AND IE-I FALL ON THE LINE IN Fig. 12;
DL-6 AND IE-7 HAVE FLAWS AND FALL
BELOW THE LINE

Fig. 7. Examples of cell structure (magnification 80×)

flaws in foams and the breakdown dependence on the rate of voltage application.

A. Some Aspects of Dielectric Breakdown in Solids

From a cursory inspection of the results, it becomes apparent that, with respect to breakdown, foams behave more like a solid than like a gas. For example, the breakdown strength E_b (kV/in.) varies as the square root of the thickness (Fig. 6), in analogy to solids; whereas, for a gas, E_b is nearly constant. Furthermore, as the blowing gas is removed, the decrease in E_b of the foam is considerably less than that for pure gas. However, there is strong presumptive evidence that breakdown is discharge initiated. If intrinsic breakdown were important, E_b would not be rate dependent (Fig. 5). In view of these observations, it appears reasonable to formally consider a foam as a solid in which breakdown is controlled by discharges in voids or flaws. Therefore, it is appropriate to discuss some aspects of dielectric breakdown in solid insulators (this part of the discussion follows closely Ref. 7).

It has become accepted in recent years that gaseous discharges frequently limit the application of many plastics with good dielectric properties. This type of breakdown is produced by electrical discharges occurring in gas-filled cavities in the body of the material, or at the edges of electrodes adjacent to the material. The cavities arise from imperfections in the manufacture of insulated components. As previously pointed out, E_b for a gas does not depend on the thickness of the layer (Fig. 1). But

Table 3. Effect of varying density and cell size on the properties of Formulations 3111-5 and 3024-17-35

Number	Density, lb/ft³	F11 content		Measurement direction						Strut thickness, mm	Length ratio (∥/⊥)	E_b ratio (⊥/∥)
		Parts by weight	%	Parallel to rise			Perpendicular to rise					
				Cell length, mm	Thickness, in.	E_b, kV/in.	Cell length, mm	Thickness, in.	E_b, kV/in.			
Formulation 3111-5, Series DL												
1	2.14	37	16.2	1.60	0.25 ±0.04	82.8 ±7.3	1.20	0.23 ±0.03	123.1 ±11.0	0.11 ±0.01	1.33	1.48
2	2.28	30	14.4	—	0.25 ±0.01	90.2 ±24.0	—	0.25 ±0.01	123.7 ±13	—	—	—
3	3.0	25	12.2	1.28	0.25 ±0.02	106.6 ±10.0	0.96	0.24 ±0.01	140.5 ±15	0.07 ±0.01	1.33	1.37
4	3.43	20	10.0	1.26	0.25 ±0.01	116.3 ±6.0	0.90	0.24 ±0.01	135.1 ±18.0	0.07 ±0.01	1.40	1.17
5	4.72	15	7.7	1.09	0.26 ±0.02	126.3 ±5.0	0.90	0.24 ±0.005	140.2 ±8	0.050 ±0.01	1.21	1.11
6	8.19	10	5.3	0.70	0.26 ±0.02	131.1 ±11.0	0.62	0.24 ±0.004	141.4 ±0.242	0.09 ±0.01	1.13	1.08
7	15.4	5	2.7	0.56	0,26 ±0.03	121.3	0.36	—	—	0.09 ±0.01	1.56	—
Formulation 3024-17-35, Series IE[a]												
1	2.29	15.0	14.9	0.96	0.233 ±0.005	104.9 ±12.0	0.70	0.236 ±0.008	153.6 ±5.5	0.035 ±0.01	1.37	1.57
2	2.52	13.0·	13.3	1.16	0.221 ±0.004	97.3 ±17.0	0.72	0.237 ±0.003	156.4 ±5.2	0.05 ±0.01	1.55	1.56
3	2.57	11.0	11.5	0.92	0.259 ±0.015	104.4 ±11.0	0.74	0.244 ±0.008	153.1 ±3.6	0.04 ±0.01	1.24	1.47
4	3.48	9.0	9.6	0.87	0.249 ±0.010	94.5 ±32	0.48	—	—	0.035 ±0.01	1.85	—
5	12.0	7.0	7.7	—	0.272 ±0.011	53.7 ±9.7	Poor sample			0.07 ±0.01	—	—
7	3.28	10.0	10.6	0.78	0.243 ±0.004	100.2 ±15.2	0.60	0.246 ±0.012	139.9 ±16.0	0.07 ±0.01	1.30	1.39
8	8.0	8.0	8.7	—	0.248 ±0.011	83.3 ±8.3	Very poor sample			0.065 ±0.01	—	—
9	1.67	—	—	1.6	0.234 ±0.01	67.1 ±22	1.03	0.254 ±0.01	106.2 ±41	0.06 ±0.01	1.55	1.34
10	1.84	—	—	2.15	0.251 ±0.02	63.5 ±14.0	1.20	0.265 ±0.02	147.5 ±16	0.04 ±0.01	1.80	2.33
11	1.45	26.2	23.6	0.92	0.232 ±0.02	61.8 ±3.0	0.73	0.228 ±0.02	130.9 ±13.1	—	1.26	2.11

[a] No data available for Series IE, Number 6.

when the layer becomes very thin, E_b starts to increase and, for about 0.2 mils, becomes comparable to that of a solid dielectric (Fig. 8). Thus, when an electric stress is applied to a solid having a gas-filled space in series with it, local breakdown of the gas will occur before the solid dielectric is overstressed. For structures of this type (Fig. 9), the voltage V_i at which discharges start is given approximately by (Ref. 7):

$$V_i = E_i \left(t + \varepsilon t'\right) / \varepsilon \qquad (1)$$

where E_i refers to the gas-filled gap of thickness t', and ε is the permittivity of the dielectric of thickness t. Breakdown will occur at some $V > V_i$; therefore, it is essential

to maximize V_i. For V_i to be high, ε of the medium surrounding the cavity must be low, and the cavity depth t' must be as small as possible. These discharge phenomena produce deleterious effects on the plastic insulation.
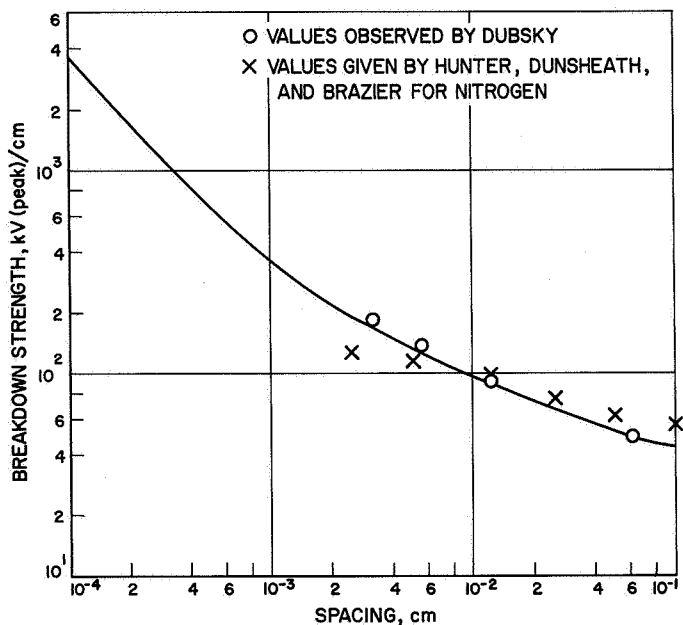

Fig. 8. Variation of breakdown strength with spacing for air at 20°C and 760 torr (data from Ref. 7 by permission of D. Van Nostrand Company, Inc.)
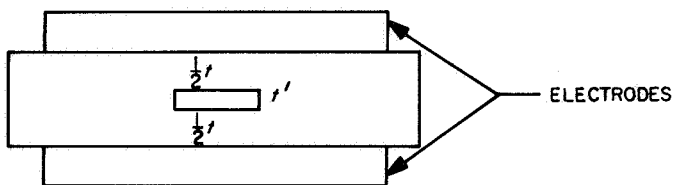

Fig. 9. An idealized void in a solid (reprinted from Ref. 7 by permission of D. Van Nostrand Company, Inc.)

Because plastics have high volume and surface resistivities, discharges that occur between opposing plastic surfaces have characteristics very different from those for discharges between metallic surfaces. The discharge current between metal electrodes flows as long as the voltage between the electrodes is maintained. For plastics, the charge that reaches the non-conducting surfaces via a discharge exerts a field in opposition to the applied field. Therefore, the discharge can pass only the small current necessary to maintain the discharge. In addition, only small areas can be discharged instantaneously,

because the charge transfer across the gap separating the surfaces occurs in 10^{-7} s, and the surface resistivity opposing the charge flow is high. Because of the build-up of charges on the cavity surfaces, a distinct difference exists in the discharge sequence under direct and alternating voltage. While surface resistivity remains high, successive discharges with dc are infrequent, but ac discharges occur in each half cycle due to the occurrence of back discharges when the polarity reverses.

B. Breakdown in *Flaws* in Foams

For purposes of this work, a foam is considered to consist of an array of gas-filled cavities. If breakdown in solids can be controlled by discharges in the relatively few ever-present cavities, then in a foam with an overabundance of cavities the same mechanism must be a virtual certainty. Since for a foam, in general, $t'/t \ll 1$, Eq. (1) becomes

$$V_i/t \equiv E_i = E_{t'}/\varepsilon \qquad (2)$$

Since ε for a foam is always smaller than that for a solid, this equation implies for a foam a somewhat higher E_i for a given cavity size. This factor involving an average property ε affects the total foam in the same way. The breakdown strength of the gas entrapped in the cell $E_{t'}$ depends on the nature of the gas, the pressure, and on the size and geometry of the cell. In general, $E_{t'}$ increases with decreasing t' (see Fig. 8) and, hence, the fluctuation in $E_{t'}$ for cavities within a volume element will be determined by the fluctuation in cell size. Thus, discharges will be initiated preferentially in larger foam cavities with a concurrent degradation of the walls of these cavities. The eventual failure of a wall will lead to the formation of a larger cavity and, hence, a further decrease in E_i. This process will lead rapidly to further increase in the size of the cavity, and ultimately failure of the foam will ensue. In summary, the size of the cavity, i.e., cell, will determine the breakdown strength of a foam. Discharge initiation will be favored in the relatively few larger-than-average cells. We refer to such cells as flaws in a foam (Fig. 10).

The correlation between the difference in breakdown strength and the anisotropy of foam structure provided the first striking demonstration of the importance of cell size. Microscopic examination showed that, in general, cells are elongated in the direction of cell rise (Table 3). Thus, when the foam is tested parallel to the direction of rise the applied electric field sees cell gaps that are greater than those in the perpendicular direction. For
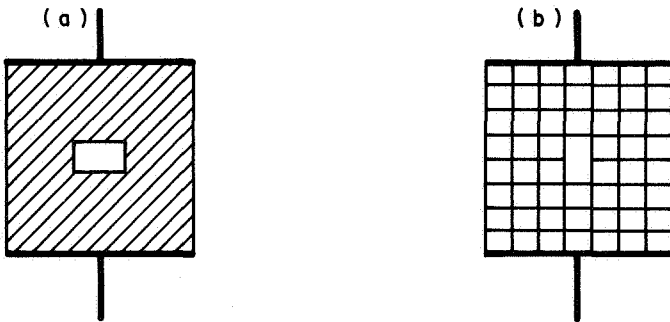
Fig. 10. A void or flaw in a foam

example, E_b versus density plots for the DL series of fluorocarbon blown foams (Fig. 11) yields two distinct curves. The higher strength corresponds to the perpendicular direction, i.e., smaller cell gap. Both curves level off for densities exceeding about 4 lb/ft³.
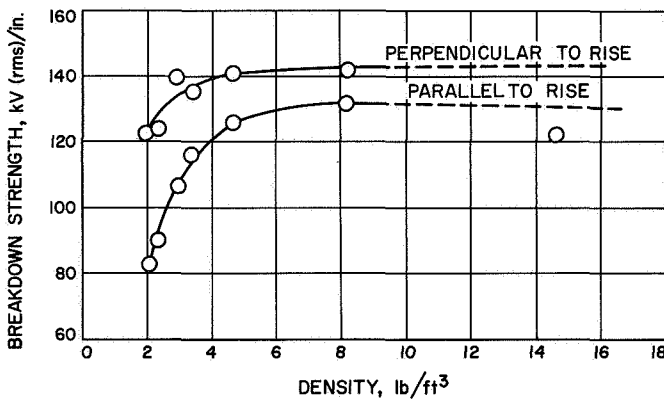

Fig. 11. Difference in dielectric strength with direction of foam rise

However, when the E_b values are plotted versus cell size a good correlation is obtained (Fig. 12). Incidentally, the straight line extrapolates to a value of about 200 kV/in. for zero cell size, a reasonable value for the bulk polymer. For drawing of the straight line, less weight was given to the low points, i.e., left from the line, because in most cases these correspond to irregular microscopic structures. An additional demonstration of the trend for a proportionality relationship between E_b and cell size is given in Fig. 13. In this figure, the E_b and the cell length ratio correspond to the two directions of a given foam; the straight line was drawn with unit slope. It should be added that Eq. (1) applies strictly to the idealized geometry shown in Fig. 9; whereas, the geometry of foam cells is more complicated. Therefore, no theoretical interpretation can be given at present to the correlations, although the general trends are clearly indicated.
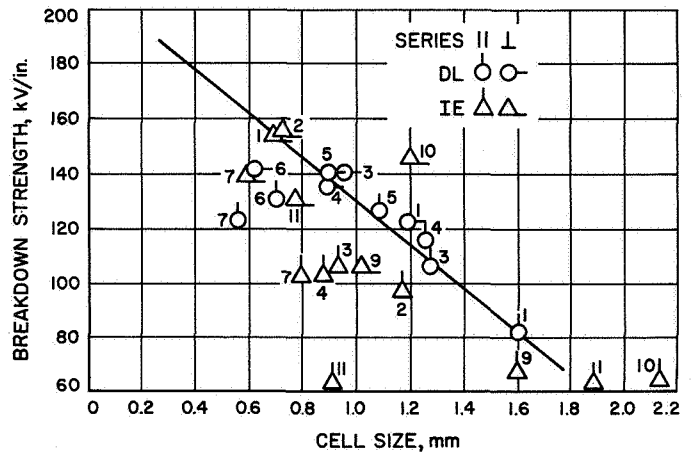

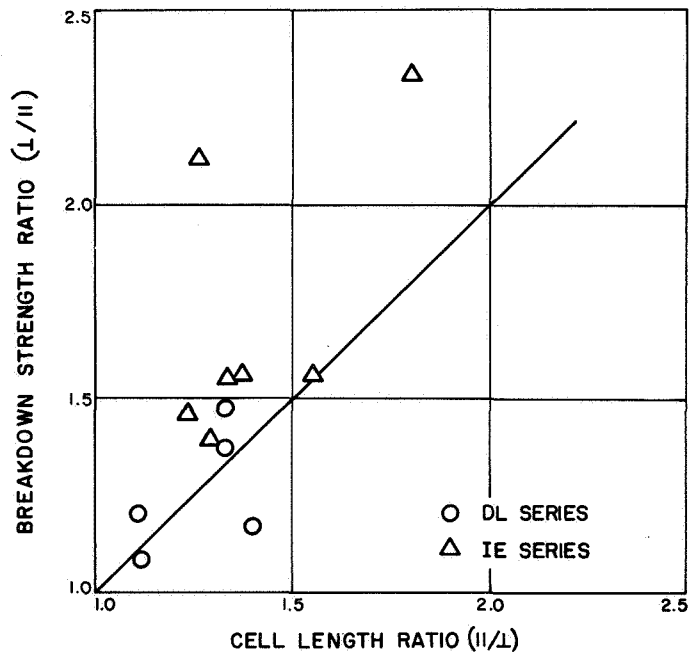Fig. 12. Variation of dielectric strength with cell size

Fig. 13. Correlation between dielectric strength and cell size anisotropy

If the breakdown strength E_b was a function of only the average cell size in the direction of test, then E_b should be independent of thickness; it is not the case, as shown in Fig. 6. The observed slopes are not unity, but are about ½. It is reasonable, therefore, to assume that breakdown will depend on the presence of *flaws* in the sense defined, e.g., multiconnected cells. The distribution of such *flaws* should follow extreme value statistics and, hence, the strength should decrease with increasing volume, i.e., thickness of the test specimen. A discussion based on extreme value statistics was presented by

Epstein and Brooks in their study of the breakdown of capacitors (Refs. 8 and 9).

C. Dependence on Rate of Voltage Application

In considering foams for encapsulant applications, the prediction of long-time behavior is of interest. Endurance tests at a constant voltage to simulate operating conditions are impractical for the purpose of screening materials, because the tests are inherently time consuming. Moreover, a statistical analysis based on relatively few test results is difficult because of the following peculiarities common to this type of test. Occasionally, specimens fail while the voltage is being brought to the test value; whereas, others may last several orders of magnitude longer than the mean lifetime.

The failure envelopes, shown in Fig. 14, illustrate this problem. The width of the band is a measure of the dispersion of the expected lifetime for a given voltage. No failure will occur below the discharge inception voltage V_i. For $V \gg V_i$, the expected lifetime falls within a relatively narrow time interval. But for V only slightly larger than V_i, the time interval during which failure may occur is large and, therefore, reasonable estimates of the mean and variance are impossible to obtain from a few tests.
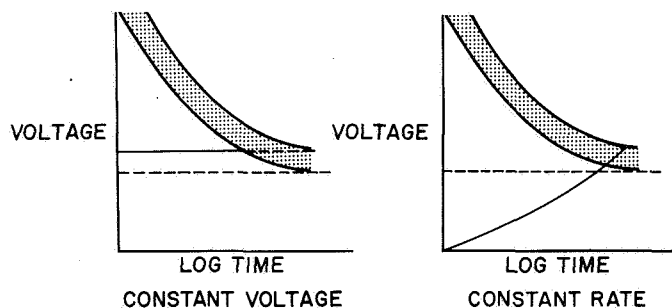

Fig. 14. Hypothetical dielectric failure envelopes

The situation is much brighter for tests carried out by applying the voltage at constant rate. In this case, the failure envelope band is approached at a sharper angle (Fig. 14), and the failure will, in general, occur within a short time interval. Fortunately, the rate dependency of failure time turns out to be directly related to the failure time at constant voltage. In the development of the appropriate relationships, this study follows the approach previously discussed in a study of electrical insulators (Ref. 10). It is of interest to point out that the problem is analogous to that of the interrelation between mechanical failure in creep and tensile failure at constant stress rate.

The basic assumption underlying the following development is that the extent of damage imparted to a dielectric during a time interval is only a function of voltage V, which is in excess of the discharge inception voltage V_i. In addition, the total damage necessary to result in failure is a constant k for a given material. These physical conditions can be expressed as

$$\int_0^\tau 1(V - V_i)f(V - V_i)d\xi = k \tag{3}$$

where τ is failure time. The unit step function is:

$$1(V - V_i) = \begin{cases} 0 \text{ for } V < V_i \\ 1 \text{ for } V \geq V_i \end{cases}$$

For any time $t < \tau$, the extent of damage D is given by:

$$\int_0^t 1(V - V_i)f(V - V_i)d\xi = kD \tag{4}$$

Clearly, for $V < V_i$, no damage will occur. For constant voltage, $f(V_c - V_i)$ is a constant and Eq. (3) becomes:

$$1(V_c - V_i)f(V_c - V_i)\tau_c = k \cdot \tag{5}$$

where τ_c is the failure time at constant voltage. For solid insulators or dielectric specimens with flaws or manufactured voids, several investigators have found the following relation to hold for test results at constant voltage (Refs. 11 and 12):

$$(V_c - V_i)^n \tau_c = k \tag{6}$$

It follows from the initial assumptions that the same functional form should hold for variable voltage. For voltage applied at a constant rate λ, the voltage V will be given by:

$$V = \lambda t \tag{7}$$

Hence, substituting in Eq. (4):

$$\int_0^t 1(\lambda\xi - V_i)(\lambda\xi - V_i)^n d\xi = kD \tag{8}$$

Carrying out the integration between 0 and τ_λ (failure time for rate λ), the result is:

$$k = \frac{1}{\lambda(n + 1)}(\lambda\tau_\lambda - V_i)^{n+1} \tag{9}$$

Thus, from test results at several rates γ, both k and exponent n can be determined. If the initial assumptions are correct, then the same parameters are applicable for constant voltage; and, hence, the lifetime of the dielectric can be predicted for any condition. It is of interest to note that an equation similar to Eq. (6) was derived by applying extreme value statistics to the problem of dielectric breakdown.

Figure 5 shows a plot of log $(\lambda \tau_\lambda - 10)$ versus log λ for the 2-lb/ft^3 foam, where λ is the rate of voltage application. The value 10 kV used for this plot is that for V_i in CO_2 at atmospheric pressure and a 1-in. gap. This value should be the lower limit to V_i in view of the small dimension of the cell in a foam. The upper limit must be below 19 kV, the lowest breakdown voltage observed for the slow rates. The plot in Fig. 5 along with Eq. (9) yield $n = 9$ and $k = 3.2 \times 10^6$. Using these values for the parameters along with Eq. (6), we estimate a failure time at constant voltage of about 5 days for $V - V_i = 2$, and about 2000 days for $V - V_i = 1$. These calculations demonstrate the necessity of determining V_i accurately to make reasonable estimates of failure time. It is planned to determine V_i by direct measurements as well as by detailed analysis of more extensive studies on the rate dependence of breakdown. Also, the interrelation between constant and variable voltage tests may break down for materials in which significant chemical degradation is induced by means of corona. The latter would be more significant in constant voltage long-time tests.

V. Conclusions and Perspectives

The following summarizes in order of importance the parameters that determine the dielectric strength of a foam:

(1) *Homogeneity of structure.* Properties of a given foam can be optimized only if the cells are uniform in size and the content of voids or multiconnected cells is kept at a minimum.

(2) *Cell geometry.* Highly symmetrical cells will minimize the anisotropy of properties. Small cell size will improve strength.

(3) *Gas content and type.* Reducing gas pressure decreases strength. Fluorocarbons lead to much higher strength than CO_2.

(4) *Polymer distribution in the cell.* It is advantageous to increase the window thickness at the expense of struts. Also, conditions during foaming should minimize stressing of windows.

(5) *Density.* The optimum density is 6–10 lb/ft^3. In this range the foam has adequate mechanical strengths, and optimization of all the above parameters is easier to achieve. It is difficult to manufacture homogeneous higher-density foams that are free of voids.

To complete the study discussed in this paper, determinations of porosity of cells, cell volume, and thickness and size of windows are being started. These determinations should provide a basis for improved correlations with dielectric strength. More studies are needed on the importance of the composition and pressure. Limited experiments have indicated that contamination of Freon II with small amounts of CO_2 drastically decreases strength. The polymer properties are expected to be of considerable importance in determining the resistance to degradation by discharges. Moreover, the polymer should determine to a large extent the stability of the foam toward high vacuum, UV, heat, and resistance to mechanical damage.

Finally, the motivation for this work was to look at corona and breakdown at low pressures. But early studies in vacuum showed that the existing knowledge of the electrical properties of foams was insufficient to permit separation of the effects of low gas pressure from other causes for failure. Since, as a result of this study, the controlling influence of the cell structural parameters on breakdown has been established, some simple considerations can be used to set a lower limit to the discharge inception voltage V_i.

Paschen's Law (Fig. 1) gives about 320 V as the potential that will initiate discharges under the most unfavorable conditions. Thus, for a foam, the corresponding voltage should be at least 320 times the number of cells. Therefore, for a foam having 1-mm cells, the minimum dielectric strengths should be about 8 kV/in. Olyphant and Meyer (Ref. 13) noted such an effect in a study on a type of syntactic foams (Scotchcast). Although these foams were highly porous, they observed a strength of 10 kV/in. at 1 torr. Their results are difficult to interpret more precisely, since neither the gas pressure inside the foam nor the porosity were determined. However, these results are encouraging.

For closed cell structures, higher values should be expected, since at low pressures the mean free path of a gas molecule cannot exceed the length of the cell. The results obtained in this study on out-gassed urethane foams (Fig. 3) are consistent with this viewpoint.

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