X-711-84-16

FORECASTING OF HIGH VOLTAGE INSULATION PERFORMANCE: TESTING OF RECOMMENDED POTTING MATERIALS AND OF CAPACITORS

(NASA-TM-85536) FORECASTING OF HIGH VOLTAGE INSULATION PERFORMANCE: TESTING OF RECOMMENDED POTTING MATERIALS AND OF CAPACITORS (NASA) 186 p HC A09/MF A01 CSCL 09A G3/33

N84-32661

Unclas 22258

Renate S. Bever

August 1984

NASA
National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

FORECASTING OF HIGH VOLTAGE INSULATION PERFORMANCE: TESTING OF RECOMMENDED POTTING MATERIALS AND OF CAPACITORS

INTERIM REPORT

RTOP-506-55-76

Task #5

by

Renate S. Bever

August 1984

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

FORECASTING OF HIGH VOLTAGE INSULATION PERFORMANCE: D.C. PARTIAL DISCHARGE TESTING OF RECOMMENDED POTTING MATERIALS AND OF CAPACITORS

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Acknowledgements.

The help,advice and actual Materials work of Dr. J.J. Park, Mr. C. Clatterbuck and Dr. B. Seidenberg, all of Goddard Space Flight Center(GSFC), is much appreciated. Much thanks is also due Mr. J.L. Westrom, formerly of GSFC, and Mr. A. Ruitberg , of GSFC, for inspiration and helpful discussions.

FORECASTING OF HIGH VOLTAGE INSULATION PERFORMANCE: D.C. PARTIAL DISCHARGE TESTING OF RECOMMENDED POTTING MATERIALS AND OF CAPACITORS

INTRODUCTION

The objective of the RTOP 506-55-76, Task #5, is to make progress toward avoiding *total* or catastrophic breakdown of insulation systems under applied high voltage in Space. To this end, non-destructive high voltage test techniques are being researched, mostly electrical methods. Emphasis is on the phenomenon of *partial* breakdown or *partial* discharge (P.D.) as a symptom of insulation quality, notably partial discharge testing under *D.C.* applied voltage. This is because many of the electronic parts and high voltage instruments in Space experience D.C. applied stress in service, and application of A.C. voltage to any portion thereof would be prohibited. Also, the literature contains relatively little published work [1, 2, 3, 4, 5] on D.C. partial discharge data and its interpretation for practical insulation systems.

Thus we

(1) Investigated the "ramp test" method for D.C. partial discharge measurements;

(2) Tested some actual flight-type insulation specimen;

(3) Used "perfect" potting resin samples and also with controlled defects for test;

(4) Used several types of potting resins and recommend the better ones from the electrical characteristics. Thermal and elastic properties must also be considered, and are mostly from the literature;

(5) Tested many types of commercial capacitors;

(6) Arrived at approximate acceptance/rejection/rerating criteria for simple test elements for Space use, based on D.C. partial discharge.

SOME BASIC THEORY ON PARTIAL DISCHARGE MEASUREMENTS

Partial Discharges (P.D.) are best defined as [6] "a type of localized discharge resulting from transient gaseous ionization in an insulation system when the voltage stress exceeds a critical value. The ionization is localized over only a portion of the distance between the electrodes of the system." The discharges may be in a void filled with gas or liquid inside a potting compound, they may be in inclusions, or they may be along a surface, or about sharp points and edges into the surrounding medium, most commonly air at atmospheric pressure. In fact, the ozone smelled around high voltage equipment is produced by exactly this type of partial discharge into the surrounding air. A more commonly known name for Partial Discharge is Corona. It is called "partial" because it does *not* extend all the way from electrode to electrode. The pulses are of very short duration, of the order of tens of nanoseconds to microseconds. They are not detectable on a D.C. microammeter or electrometer, and when this type of instrument begins to show a tiny, wavering, average D.C. current, one can be sure that the test sample is already in catastrophic breakdown or suffering very intense, rapidly repeating partial discharge pulses. The detection of individual partial discharge pulses requires sensitive instrumentation to be discussed later.

It is impossible here to go into the detailed discussion as in the excellent book by F. Kreuger [7], but some important points might be brought out here: If the void is filled with gas, then Paschen's curve regulates the inception voltage and extinction voltage, as a function of pressure inside the void and the electric field in the void and the geometric descriptors of the void. (The word "void" is used here for any gas-filled cavity whether bubble or thin, large-area delamination.) Ionization of individual atoms can occur by collision with an energetic particle carrying the required ionization energy (for instance, 13 electron volts for a hydrogen atom). But to set off a momentary avalanche discharge requires, even at the Paschen minimum pressure, at least two hundred volts across the void. Figures 1, 2 are examples of

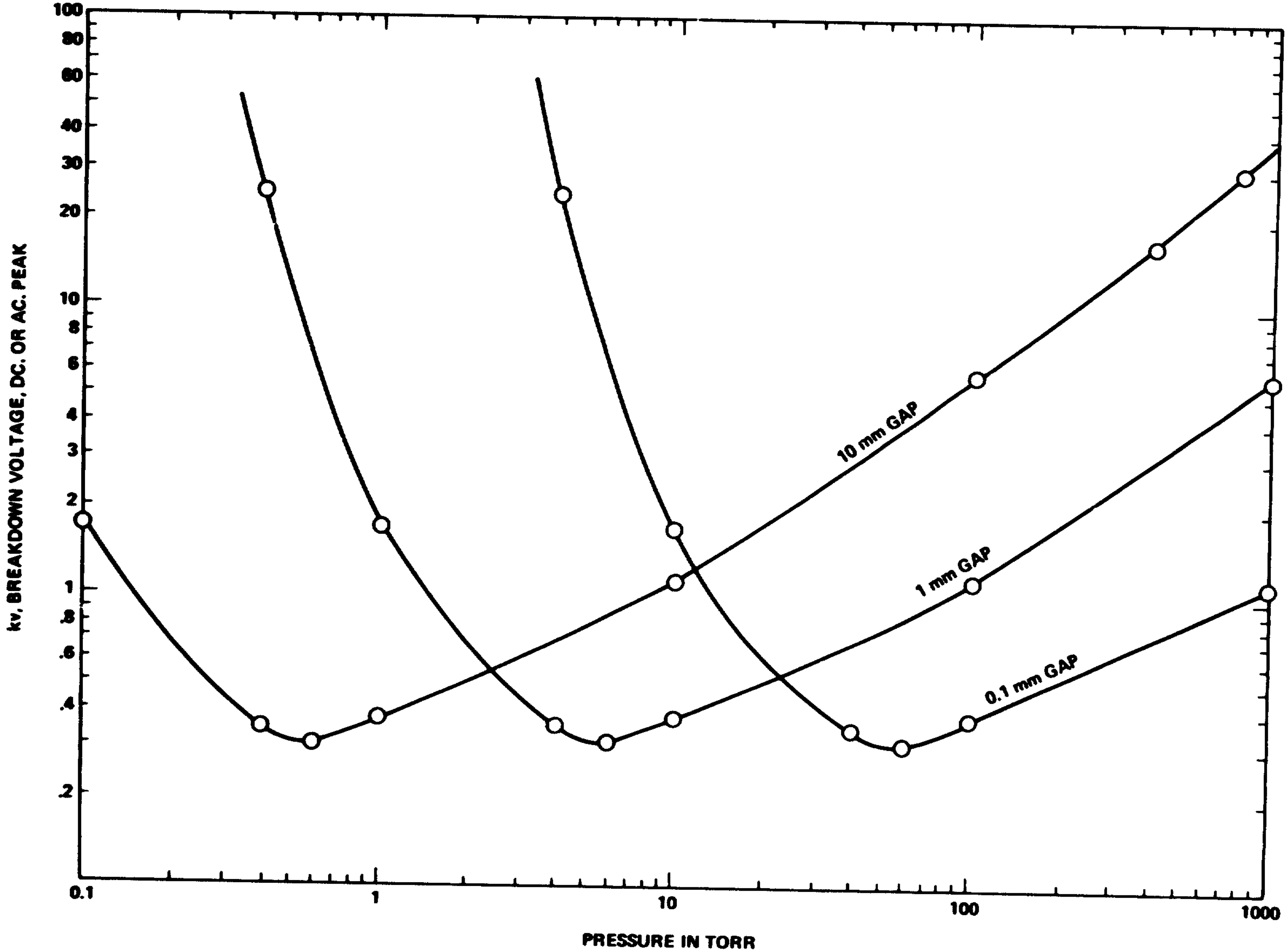

Figure 1. Paschen's Original Curves. Breakdown Voltage in Air as a Function of Pressure. (Iron Electrodes)

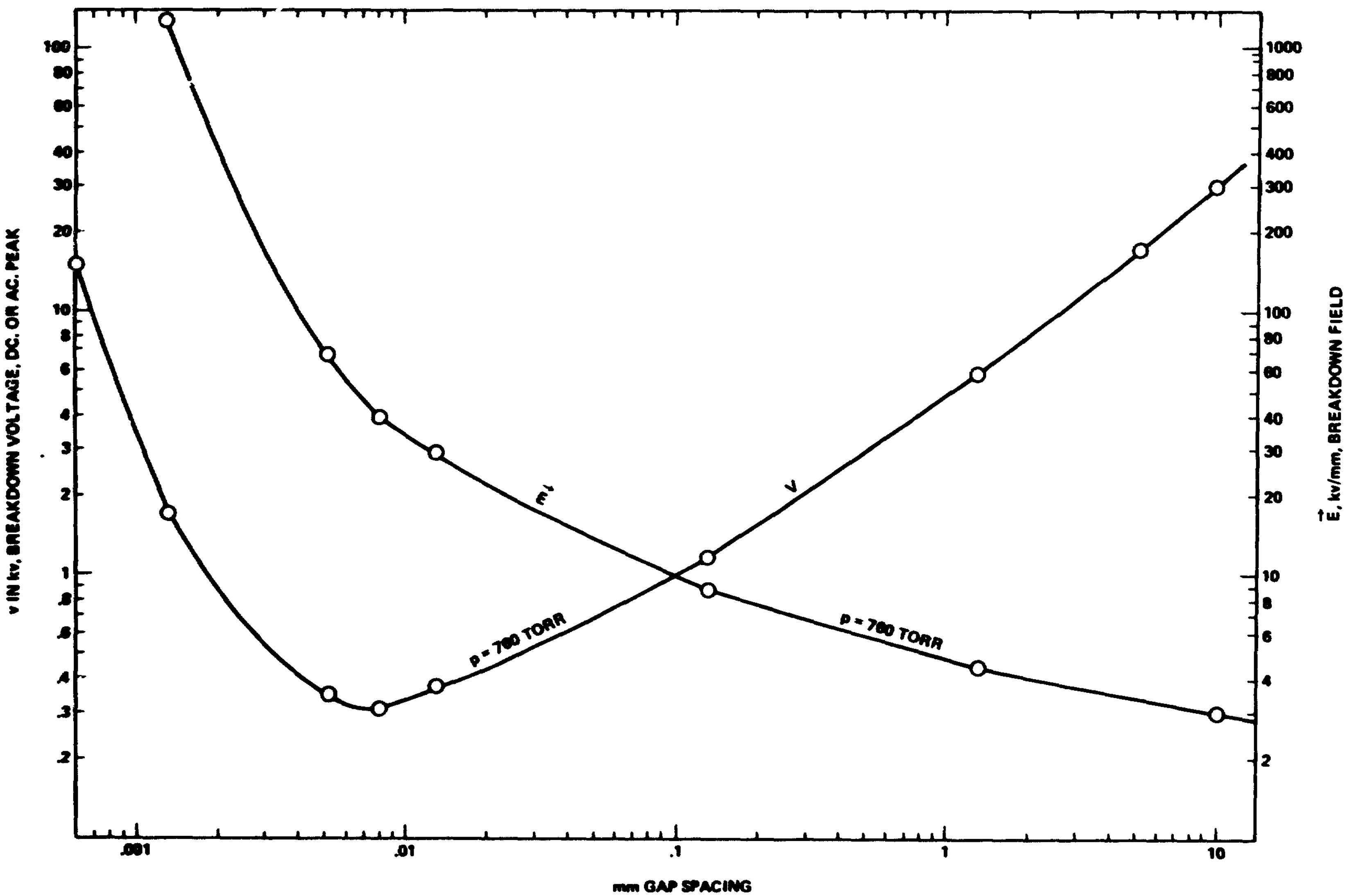

Figure 2. Paschen's Curve, V. Field Strength Curve, E. (Iron Electrodes)

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Paschen's curves, with parallel electrodes in air. There exist convenient theoretical adaptations of these for voids in dielectric materials. [8, 5]

A.C. versus D.C. testing

The equivalent circuit of a void in a dielectric under A.C. applied voltage is given in Figure 3a. The recurrence of internal discharges as a function of applied A.C. voltage is shown in Figure 4, [9]. As applied voltage v_a across the entire sample rises, so does the voltage across the cavity, v_c. When this reaches the breakdown voltage U^+ a flow of free charge occurs in the cavity, causing a drop in v_c across the cavity down to V^+: All this occurs in about 10^{-7} seconds. If total applied voltage to the specimen, v_a, is still on the rise, then the v_c will increase again also, until it reaches U^+ again, and there will be another discharge. The field across the cavity is determined by the superposition of the main applied electric field causing fixed polarization charges in the dielectric lining the cavity walls and the field of the free surface charges at the inside of the cavity walls, left behind just after the last discharge. Just after the last discharge these fields counteract one another: the polarization charges and free charges adjacent to one another on the same wall almost neutralize one another until the *increasing* applied voltage or the *change in polarity* of the A.C. voltage makes the charges on the cavity wall increase in quantity again and predominate again until their field causes another breakdown of the cavity or a second pulse. In the *D.C.* case, however, one has to wait until more charges in the dielectric medium lining the cavity are placed there by *conduction* through the dielectric. Since the conductivity of a good dielectric is very low, this takes a long time. Hence, at applied electric fields at which a sample begins to show regularly spaced pulses at A.C. applied voltages, discharge pulses at D.C. voltages are few and far between, and might in fact be missed altogether (if data acquisition time is not long enough). Observation of P.D.'s on D.C. voltage must be made with a storage oscilloscope and counters as described below. Thus partial discharge detection under D.C. conditions is more difficult and time consuming.

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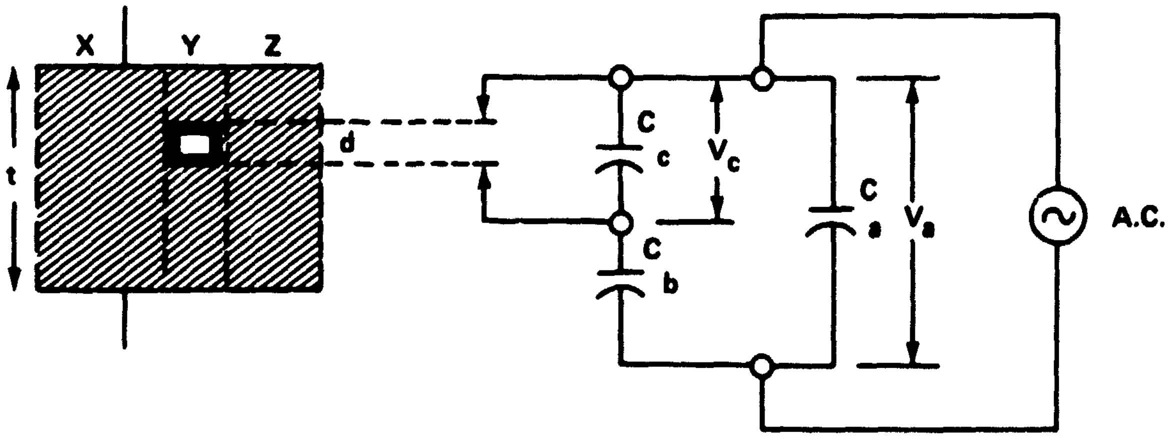

Figure 3a. Left: Dielectric with Void.
Right: Equivalent Circuit of Void in Dielectric for AC Partial Discharge Testing.

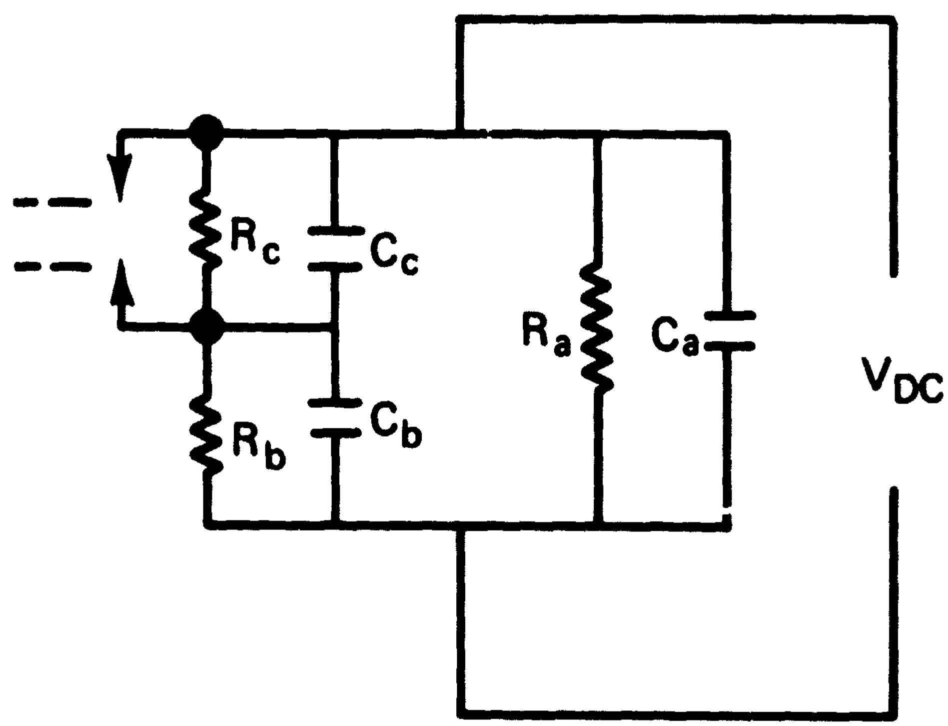

Figure 3b. Lumped Parameter Circuit Model of a Cavity for the DC Partial Discharge Case.

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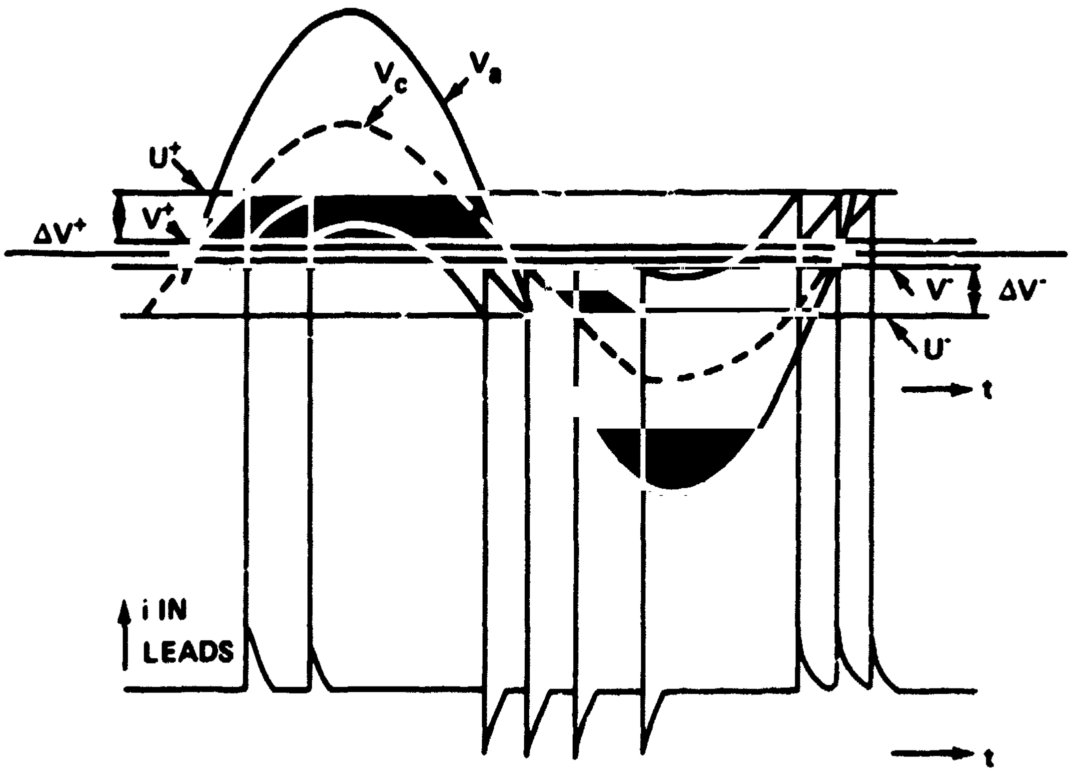


Figure 4. AC Partial Discharge Testing. Applied waveform v_a, voltage across the cavity v_c and current in the leads i, as a function of time t.

but it is much less damaging. Very little heating of the test specimen occurs under D.C. conditions as compared to the heat generated with A.C. voltages. Also, samples should be tested under the same conditions as in service, which for Space use is often D.C. Moreover, the very fact of only a few pulses during D.C. is a safety factor, as compared to thousands of pulses per minute, already at the discharge inception voltage under A.C. conditions, each pulse doing a little damage.

Brief mathematical models for a cavity in a dielectric medium for D.C. and for A.C. applied voltage is given in Appendix I.

EXPERIMENTAL METHOD

A block diagram of the essentials of a P.D. measurement facility is shown in Figure 5, and photographs of some of our facility are shown in Figures 6a and 6b.

Several questions arise and need to be dealt with as to the circuit arrangements for detecting the tiny P.D. pulses: general outlines of basic circuitry are given in ASTM D 1868-81 and IEEE Std 454-1973 [6, 10]. More specifically:

(1) What is the detection impedance Z that translates the small current surges in the test specimen cables into measurable voltage pulses?

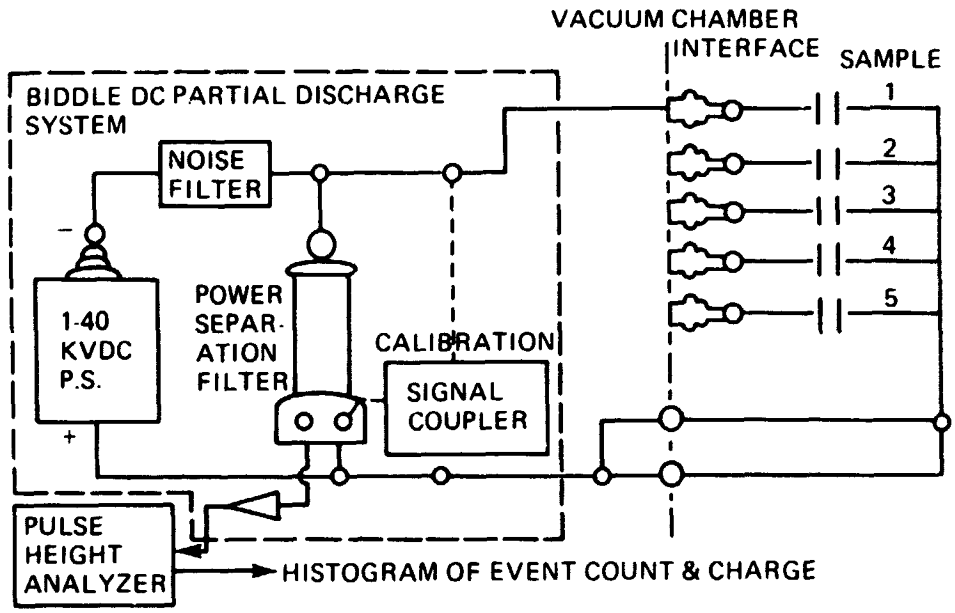
a. One can use a resistor R in parallel with a small capacitance C: this RC network can be the feedback network of a charge-sensitive operational amplifier, the C acting as an integrating capacitor for the charge. The voltage pulse across the combination will be unidirectional.

A proper preamplifier must be used with proper input characteristics and low noise levels, so as to permit the tiny fast voltage pulses to pass through without attenuation or obliteration.

b. One can use a tuned LCR input network, which is the method used by the James G. Biddle Co. P.D. Detection System used in these experiments. The corona impulse sets off shock oscillations, the first negative half of which is integrated and amplified (attention to bandwidth of amplifier.)

(2) What is the detection sensitivity of different arrangements of the circuit components? Detection sensitivity is defined as the fraction of the terminal corona-pulse voltage that appears across the detection impedance Z for measurement.

This has to be answered by a proper calibration method preceding the testing with each new test sample inserted. Analysis has been done by several authors [1, 9, 11].



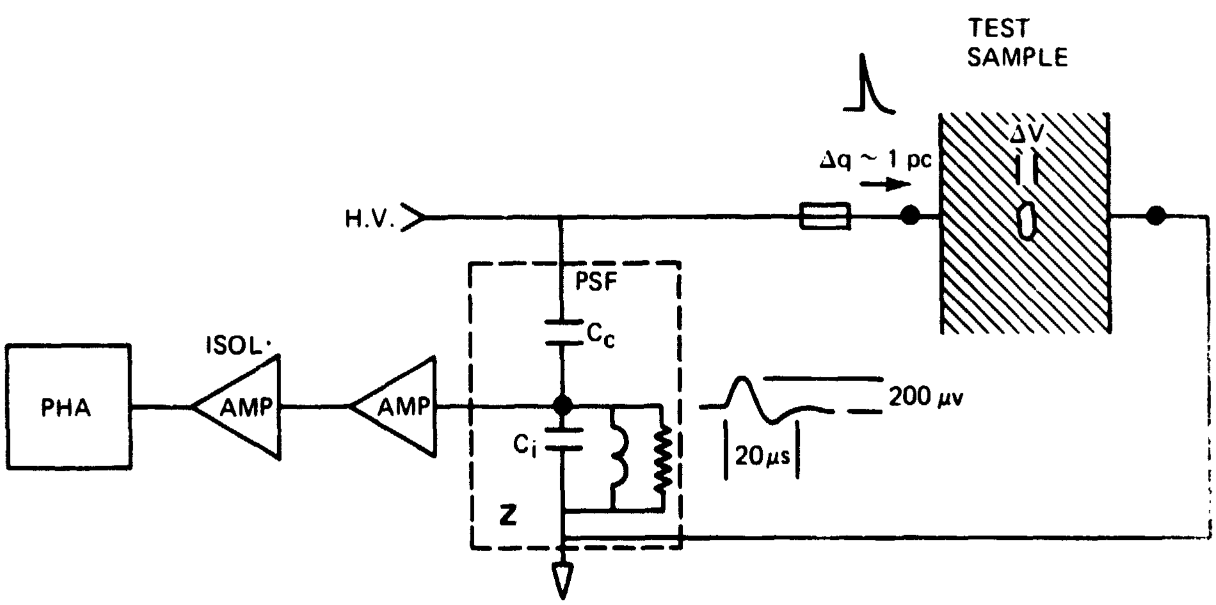


Figure 5. Test Set-Up for Measuring DC Partial Discharge.

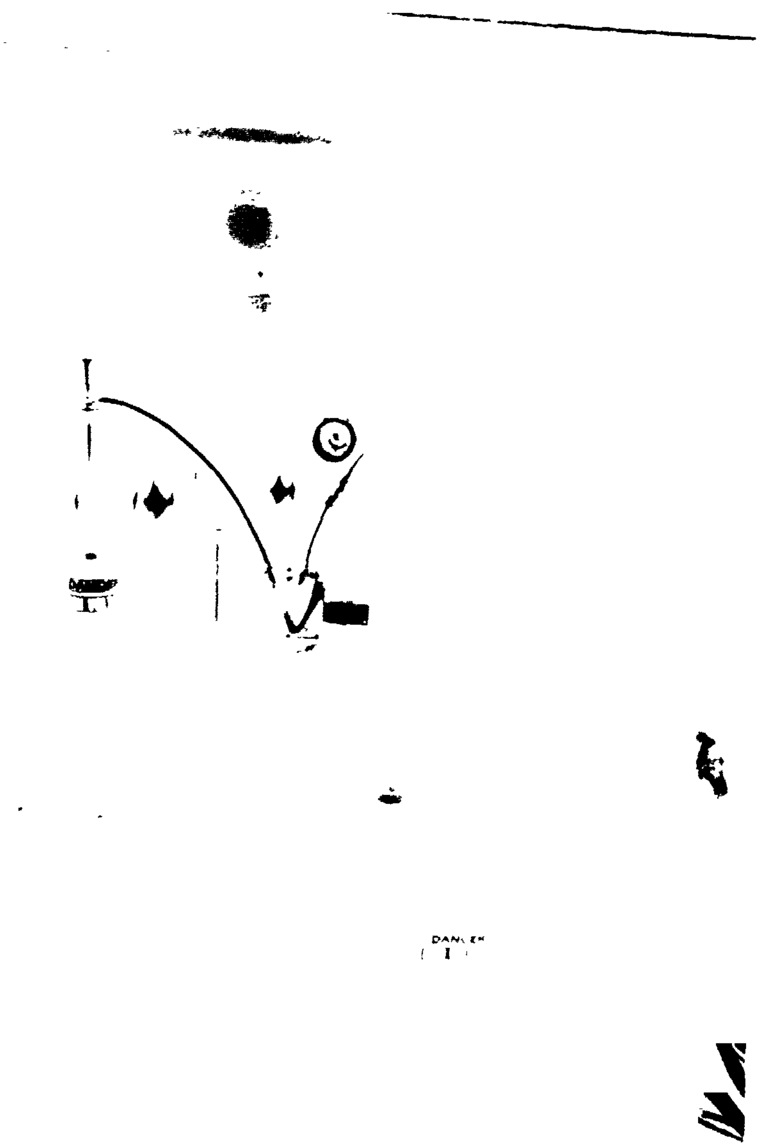


Figure 6a. D.C. High Voltage Test Cabinet.

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Figure 6b. D.C. and A.C. Control Circuitry and Multichannel Analyzer.

Two sets of commercial equipment have been employed by us for work reported herein:

I.) Earlier on, a borrowed facility located several miles away from Goddard Space Flight Center was used. It consisted of a 664 000 series, ±40 kv, 3 ma D.C. power supply and partial discharge detection system by J.G. Biddle Co. of Blue Bell, Pa. The output pulses were coupled via buffer-isolation amplifier to a ND-100 multichannel analyzer made by Nuclear Data Corporation of Schaumburg, Illinois. Vacuum capability was available.

II.) With moneys provided by the 506 RTOP a new facility was recently established at Goddard Space Flight Center. It consists of a 664 000 series, ± 60 kv, 5 ma D.C. power supply and P.D. detection system by Biddle Co. and a ND-65 multichannel analyzer by Nuclear Data Corporation.

A.C. and A.C.-D.C. superposed capability are now also available, but work with that is not reported in this document.

Vacuum system is a planned addition for this year.

All measurements are made in an electrically shielded room with its own isolated and filtered power lines The test sample is either immersed, including cable ends and metallic couplings in Fluorinert FC-40 (3M Co.) electronic liquid, or in a 10^{-6} torr vacuum. Care is taken to see that cablings and vacuum feedthroughs are corona free.

As discussed in the theory section, during the act of voltage rise, if this goes above P.D. inception voltage and a rise time is fast compared to the time constant for establishing an equilibrium voltage distribution, then many more discharges will occur during the voltage step and for a short time following it than on the quiescent voltage plateau. In essence the voltage rise corresponds to ¼ A.C. cycle, the voltage distribution is capacitative rather than resistive and the blocking space charge is not yet equilibrated. For these reasons, D.C. partial discharge testing has been investigated as a stepwise ramp-plateau sequence rather than just one quiescent measurement at the rated voltage of the test object.

The ramp-plateau sequence generally consists of dividing the voltage range from 0 to maximum into sections. For example, if maximum voltage is 8 KV, then the first ramp would be from 0 to 2 KV in 10 ± 2 seconds while acquiring data, followed by a 2 minute wait, followed by a 100 second acquisition of pulses at 2 KV, then the next ramp and plateau, and so on and so forth to 8 KV. Finally the voltage is reduced to 0 in 10 seconds, but collecting data for 40 more seconds to obtain all the relaxation counts. Or, one can go up in steps of ½ rated voltage V_R and such a time profile is illustrated in Figure 7.

It must be stated here immediately that the P.D. pulses acquired during voltage increase or ramping are due to the test sample and *not* due to "noise" on the autotransformer of the power supply. Any such noise has been filtered out by two stages of filtering between the Biddle power supply and the power separation filter of the detection system. Verification tests of this have been carried out on capacitors of the same capacitance and voltage rating, but made by different manufacturers [12].

RESULTS

I. Influence of Ramp Test Variables

These variables are ramping speed, length of sojourn at intermediate plateaus, and interpolation of voltage at which P.D.'s first appear upon ramping. Initially one has to obtain reasonable repeatability of baseline P.D. histograms on the chosen test sample under constant conditions. Of course, one must never expect exact repeatability from P.D. measurements since the discharge phenomenon is a probabilistic process. Also, as discussed above, for good dielectrics, if the voltage is raised over the same voltage range a second time, immediately following a first time up, then the P.D. activity is much reduced due to the injected space charge and possible ferroelectric effects. Nevertheless, a once per day P.D. run on a tubular mylar capacitor of 10,000 pf, 8 KV rated voltage mounted in a continuous 10^{-6} torr vacuum was reasonably repeatable after several days. Between runs the capacitor remained shorted to

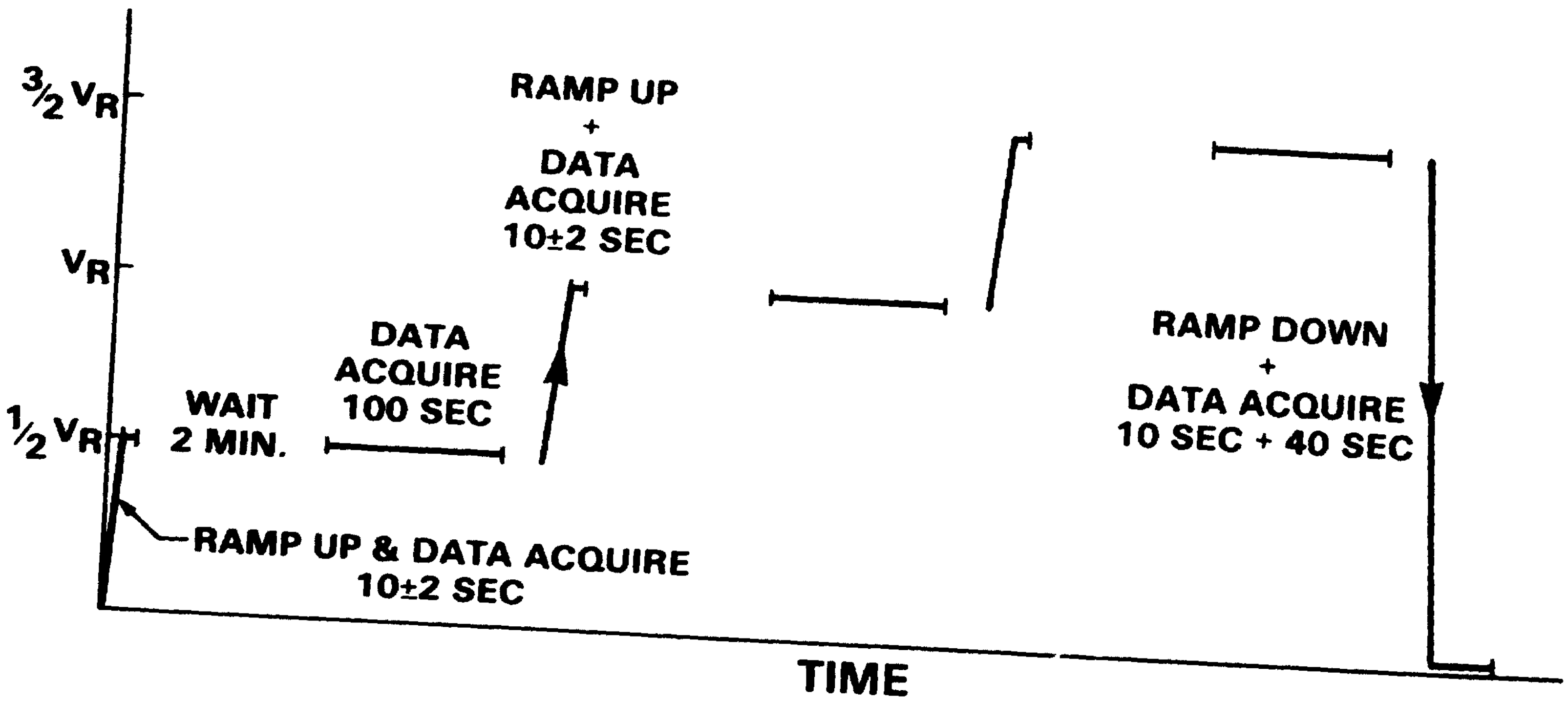

Figure 7. Typical Ramp Test Time Profile for D.C. P.D. Measurements.

ground. Thereafter, one change in the ramp test schedule was made in the once per day run.

Summarizing the findings gives: 1.) For a first approximation, ramping speed on a "stabilized" test specimen has only a small effect within the range of present usage. That is, whether $\Delta V/\Delta t$ is 2 KV/1 second or 10 seconds or 40 seconds does not influence corona much more than data spread at the *same* speed from one measurement to another, providing one acquires counts for a few seconds after the ramp is finished. 2.) A closer look reveals that (a) fast ramping evokes somewhat more counts; (b) fast ramping produces more high energy pulses; (c) a ten second part-way ramp is a reasonable choice for practical operation within our 60 KV available range of voltages. 3.) A single ramp to rated voltage in the same time as the sum of the part-way ramp times causes slightly fewer total pulses and these are shifted somewhat toward the lower energies, surprisingly. 4.) The voltage range upon ramping within which the very first few low energy P.D.'s appear, corresponds closely to the A.C. inception voltage at the 10 picocoulomb (pc) level. Table 1 illustrates this aspect.

The conclusion is that for any one comparative study of partial discharge characteristics a strict and consistent time regime should be adhered to. Nevertheless, the small change of P.D. counts with a 40-fold change of ramping speed indicates that relatively little error is introduced even with manual ramping, and that large differences in P.D. behavior as seen below are truely characteristic of the test specimen. Furthermore, in the absence of an AC high voltage power supply or when AC applied voltage is undesirable, then a good estimate of the AC inception voltage of corona can be obtained as the DC voltage where pulses first appear upon ramping, as shown in Table 1.

II. Faint Object Camera (FOC) Study

We used D.C. P.D. measurements as comparative tests to improve the Westinghouse de-

Table 1. Comparison of D.C. ramp and A.C. partial discharge CIV on some commercial capacitors.

Sample description	D.C. voltage ramp where pulses first appear 2 pc level, 3 pc level	No. of pulses/ 10 sec. ramp	A.C. inception voltage at the 10 picocoulomb level
Ceramic caps. 720C8109: 1200 pf 40 KV rated			
S/N 70	17.5 - 20 KV	(1 pulse)	23.8 KV peak
S/N 71	27.5 - 30	(1)	Above 26.6 KV peak
S/N 72	10 - 12.5	(1)	14 KV peak
800 pf, 35 KV rated			
S/N 73	15 - 20 KV	(1 pulse)	20.3 KV peak
S/N 74	10 - 15	(6)	17.5 KV peak
S/N 75	20 - 25	(4)	25.9 KV peak
Cylindrical Mylar caps B32237, 10,000 pf, 8 KV rated			
S/N 8	0 - 2 KV	(13 pulses)	2.5 KV peak
S/N 9	0 - 2	(45)	1.9 KV peak
S/N 10	0 - 2	(1)	2.5 KV peak
S/N 12	0 - 2	(26)	2.2 KV peak
Flat, encapsulated Mylar caps. B32227 10,000 pf, 6.3 KV rated			
S/N 13	0 - 2 KV	(234 pulses)	0.38 KV peak
S/N 14	0 - 2	(104)	0.45 KV peak
Impregnated Micapaper KMR 1A 3533SP-5 10,000 pf, 8 KV rated			
S/N 19	0 - 2 KV	(4 pulses)	3.0 KV peak
S/N 18	2 - 4	(1)	4.0 KV peak
S/N 17	2 - 4	(10)	2.7 KV peak

sign of the packaging of the FOC vidicon tube of the Space Telescope satellite as illustrated by Figure 8. The two main tasks were (1) essentially to aid in choosing the most suitable potting compound and (2) investigate the front end design and improve it around the NESA (Non-Electrostatic Application) guard plate (1/8" thick glass with thin conductive transparent coatings on both sides, leaving a narrow rim uncoated). The general approach was to manu-

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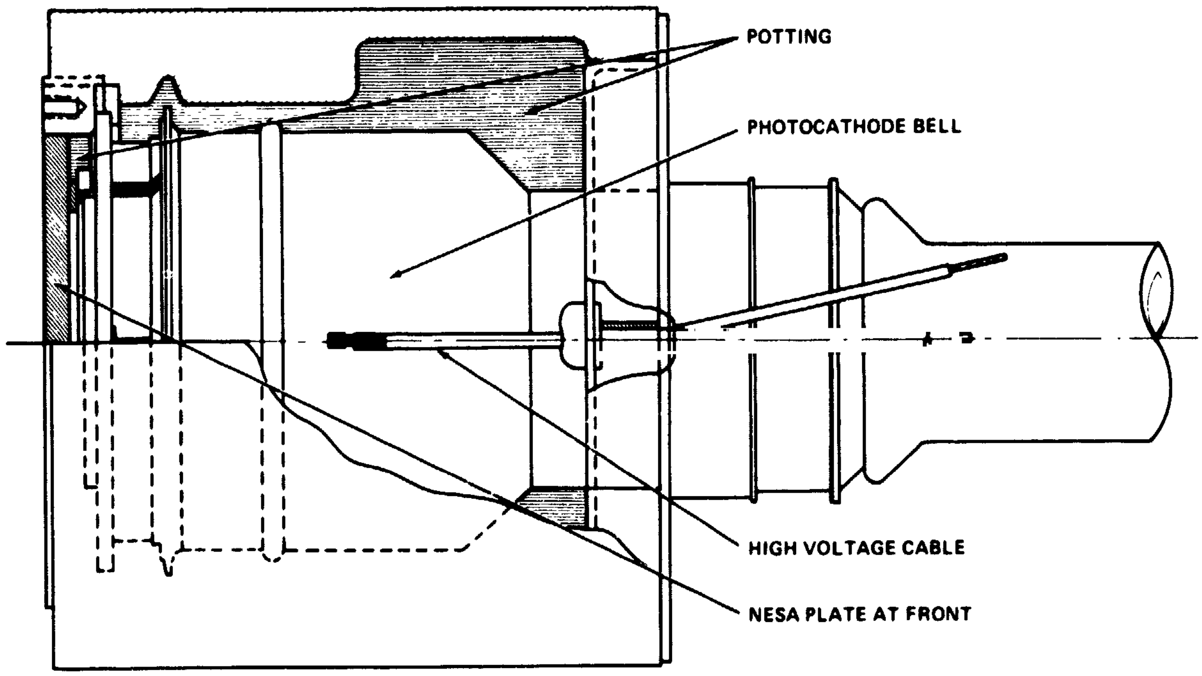

Figure 8. Early FOC vidicon tube packaging design. Courtesy of FOC, Space Telescope project.

facture realistic witness samples, in the case (1) of several potting compounds around the actual photocathode bell, in the case (2) of three different front-end simulations. After manufacture, a baseline P.D. test was done in high vacuum. Then all samples were thermal cycled in air from – 20°C to + 45°C at least 10 times to exacerbate defects and thermoelastic stresses. This was followed by another P.D. test in vacuum, then a Life test of at least 1000 hours at – 17.5 KV in vacuum, followed by another P.D. test. An extensive report is published elsewhere [13]; only a few details can be given here. Figure 9 shows one of the results: a marked change in P.D. histograms on the Qualification Unit #1 occurred when the front side of the NESA plate was left floating, (high voltage was on the inner-side), compared to when it was grounded. Now P.D. pulses at much lower voltages appeared than before, warning of trouble to come. Indeed, catastrophic breakdown occurred at 10 KV. Physical examination

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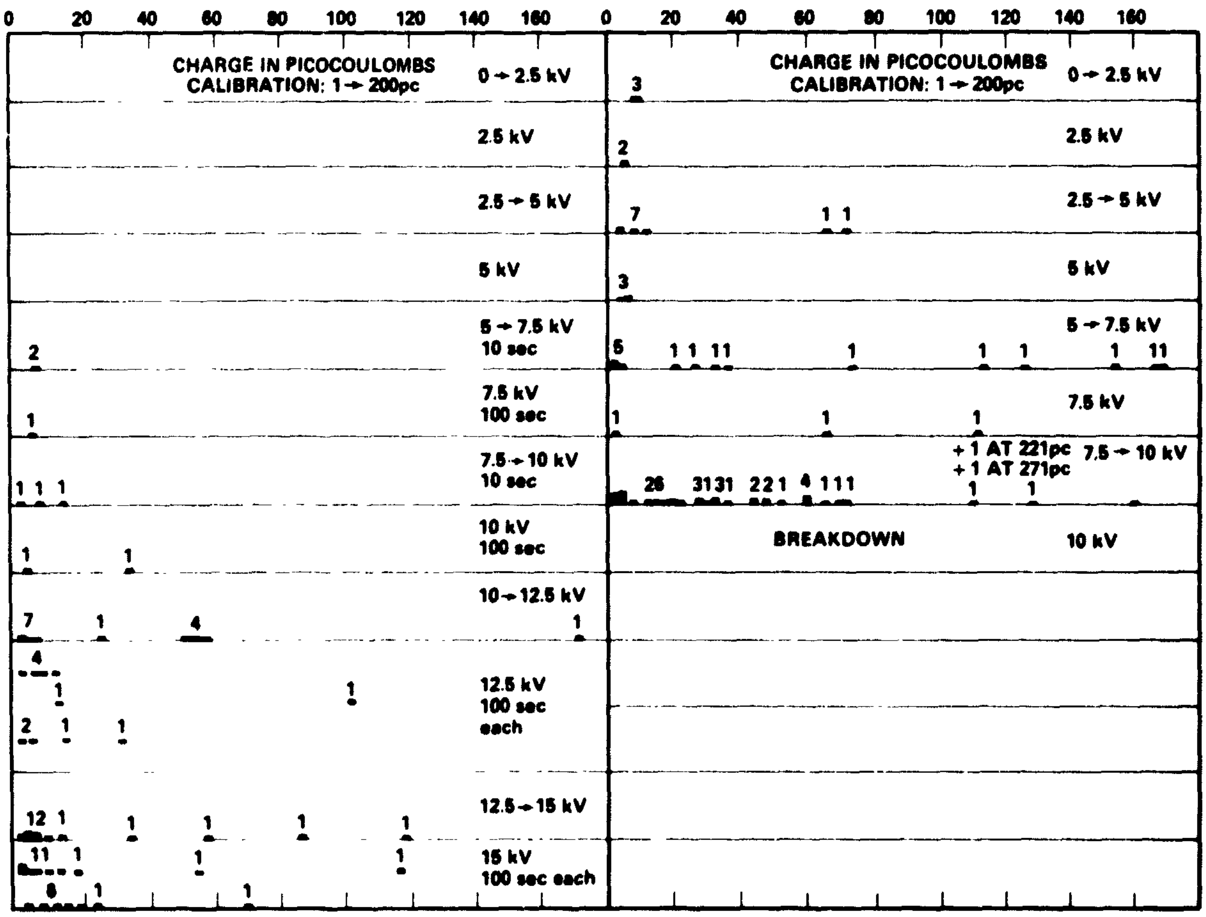
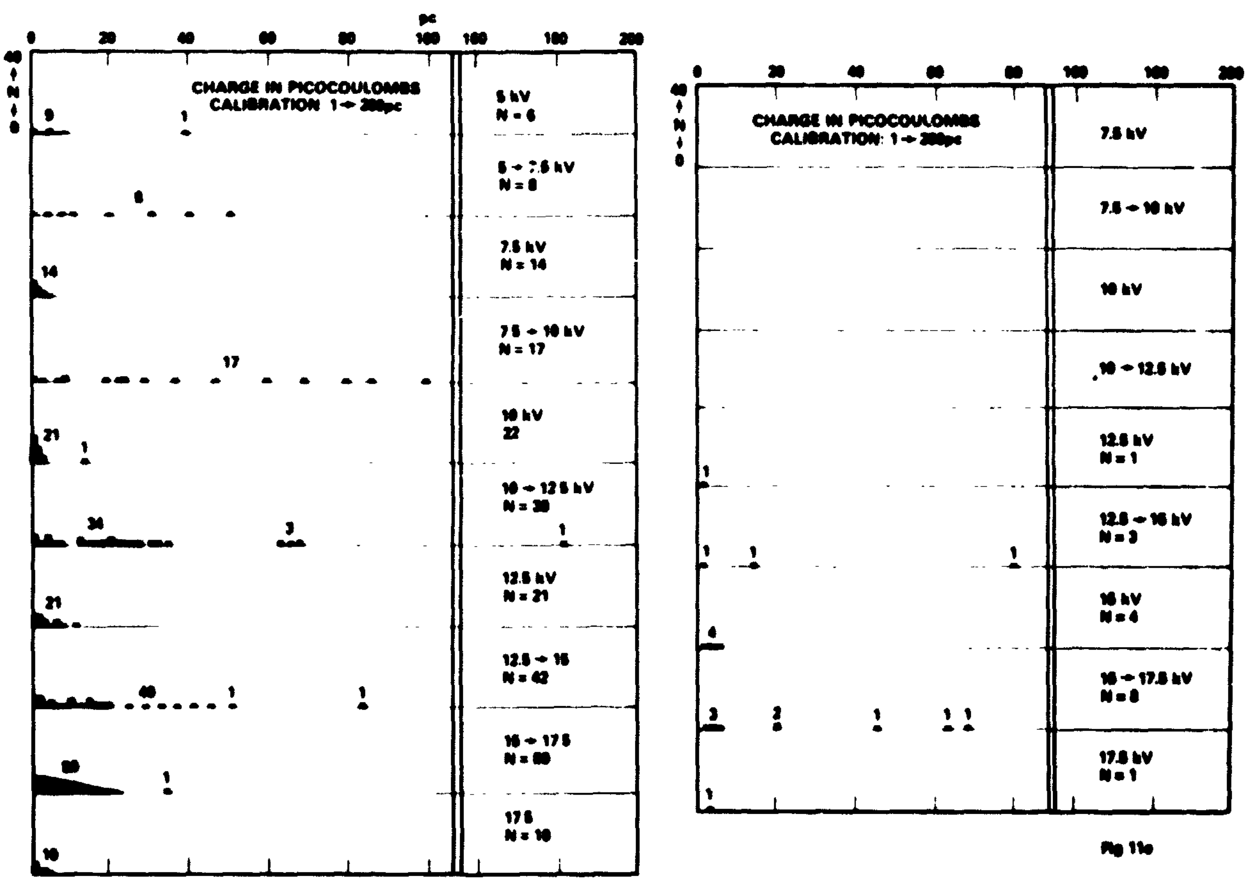


Figure 9. P.D. histograms of Qualification Unit #1 comparison of NESA plate floating (left) and NESA plate front surface grounded (right).

of the sample later showed this *not* to be a bulk breakdown, but a surface problem at the glass-potting interface where there was bad adhesion.

Figure 10 shows comparative histograms of potting with CPC 41 polyurethane (left) and Uralane 5753 LV (right), both with primers, and after both had been subjected to 20 thermal cycles and tested after 1½ hours in high vacuum. Clearly Uralane was the more desirable potting compound.

When relatively high conductivity (10^{-11}/ohm cm) polyurethane Feldex R-6 was used as packaging around the front end, then two interesting things were observed. One was that now more P.D. pulses occurred on the 100 second quiescent dwells at constant voltage than on the 10 second ramps. The other was (having inadvertantly trapped two large bubbles at partial pressures on the overhang of the NESA plate and on its high voltage side) appearance of P.D.'s at − 17.5 KV in the several thousand picocoulomb range. rather than the usual several hundred pc's. Figure 11 shows the histogram (taken here at − 40 KV in FC − 40 liquid and for 600 seconds for puposes of emphasis.) End of scale calibration is 8000 pc. and the histogram emphasizes two peaks of large picocoulomb content.



CPC-41

URALANE 5753 LV

Figure 10. P.D. histograms of CPC-41 (left) and Uralane 5753 (right) potting of cathode bell, after 20 thermal cycles, tested after being in 10^{-6} torr vacuum for 1.5 hours.

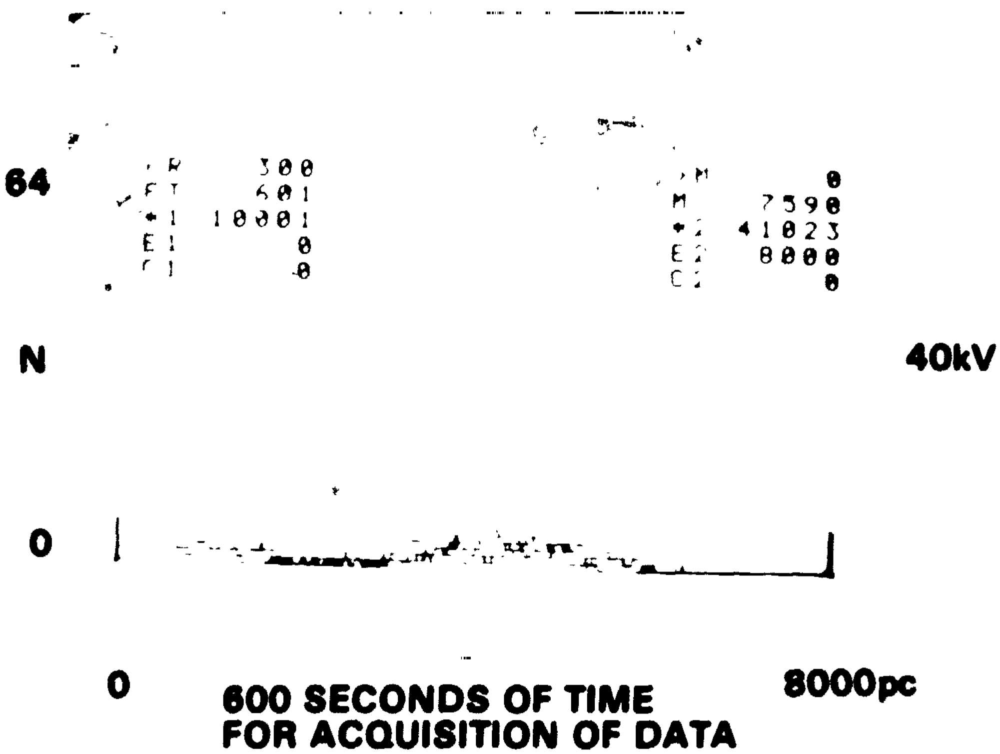


Figure 11. P.D. histogram of front-end NESA plate witness sample potted with Feldex R-6. Voltage - 40 KV, data collective time 600 seconds, calibration 30 → 8000 pc. Sample immersed in Fluorinent FC-40 for test.

III. Potting Materials Study

It seemed desirable to do a more systematic D.C. partial discharge study on candidate potting materials, cast in very simple geometries. To show the bewildering variety of resins to choose from, a table reproduced from Wm. Dunbar's 1979 report [14] is given in the Appendix II as Table 2. One can summarize the most desirable properties as target properties and these are given in Table 3. An additional criterion to help in selecting out the most desirable resins for high voltage potting compounds is low Shore hardness. In this way, the cured resin can be dug into to repair embedded circuitry and/or the softer resin formulations can aid as cushioning against the vibrations of launching. Table 4 lists the materials tested in this study.

One of the selected resins is *devolatilized* RTV 615. The devolatilization was done by

Table 3. Target Properties for High Voltage Potting Materials

Electrical properties:		
Arc resistance	>	60 seconds
Dielectric constant	<	6
Dielectric strength	>	350 volts/mil
Surface resistivity	>	10^{12} ohm
Volume resistivity	>	10^{12} ohm-cm
Other Physical Properties		
Shrinkage	<	3%
Age shrinkage	<	0.5%
Service temperature	–	55°C to + 105°C
Heat distortion temperature	<	100°C
Coefficient of Thermal Expansion	<	1.5×10^{-4} °F
Outgasing: Total weight loss	<	1%
Condensibles	<	0.1%
Maximum cure temperature	<	100°C
Pot life	>	30 minutes

placing 2 lb of the RTV 615 resin into a 10 inch diameter by 2 inch deep aluminum pan, which gives a 0.5 inch depth of resin. This was brought to a 10^{-5} to 10^{-6} torr vacuum and heated for 24 hours at 150°C, as measured by a thermocouple junction in the resin. Subsequently the viscosity had increased by 10% and the outgasing was decreased to less than 1% total weight loss and less than 0.1% condensibles. The latter is the desired result of the devolatilization.

Table 4. Potting Compounds Considered in this Study, the First Four of Shore A Hardness, A ≅ 50.

Potting Resin:	Primer:	Volume Resistivity in ohm-cm: 25°C	Dielectric Constant: 25°C	Coeff. of Thermal Expansion per °C	Glass Transition Temp. Tg
DC 93-500	DC 93-060	6.9×10^{13} (6.2×10^{14})	2.7 at 0.1 Mhtz (.0016)	$\frac{300 \times 10^{-6}}{°C}$	- 115°C
Uralane 5753 LV	PR-1	1.2×10^{16} (2.3×10^{16})	2.9 at 1 Mhtz (.017)	$\frac{150 \times 10^{-6}}{°C}$	- 6.5°C
CPC 41	PR-1	$\sim 10^{12}$	3 at 1 Mhtz		
FELDEX R-6	PR-420	$\sim 10^{11}$	5	$\frac{180 \times 10^{-6}}{°C}$	
Conathane EN-11 (Too hard) (Elevated temperature curve)	PR-1 PR-1	4.3×10^{15} at 25°C; *but* 4.8×10^{11} at 130°C	2.9 at 1 Mhtz	$\frac{140 \times 10^{-6}}{°C}$	- 75°C
Devolatilized RTV 615	DC 93-060	4.5×10^{13} (1×10^{15})	3.0 at 1 Khz & 100 hz	$\frac{\sim 270 \times 10^{-6}}{°C}$	- 120°C
2B74 Polyurethane		1×10^{15}	2.9 at 1 Mhtz 4.2 at 100 hz	$\frac{100 \times 10^{-6}}{°C}$	
Hysol PR 18M		2×10^{13}	3 at 1000 Mhz		

The material samples were cast in simple circular discs which would easily lend themselves to introduction of controlled-sized voids. However, not being constrained, these samples could not be thermoelastically stressed as could the FOC concentric-cylinder, case (1) type witness samples.

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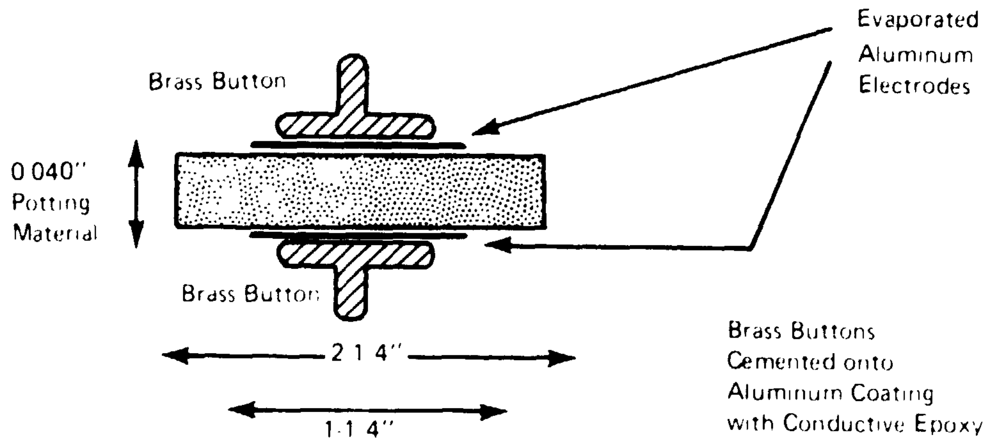
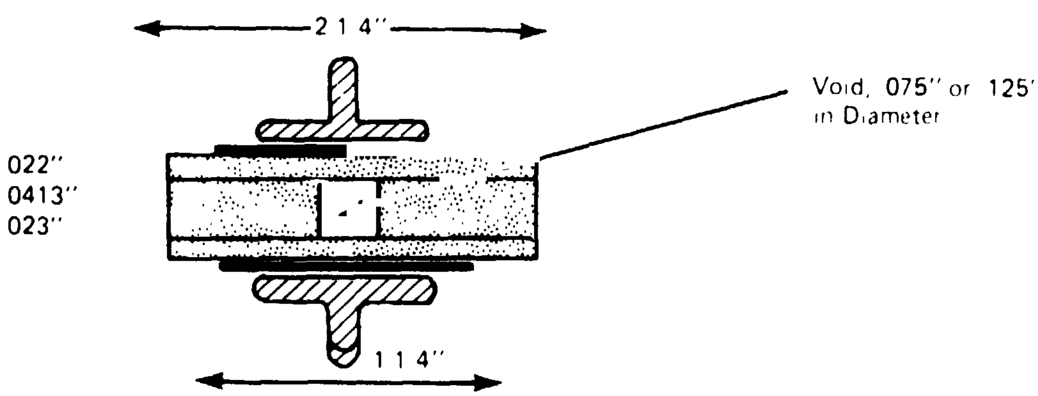
(a) So-called perfect samples, 0.040 inches thick.

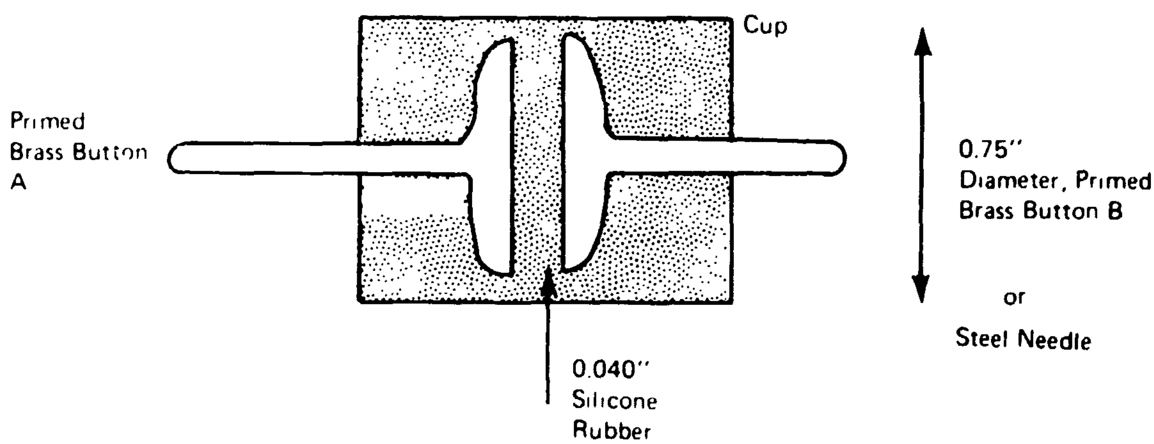


(b) "Imperfect", 3-layered sandwich samples with pillbox void purposefully introduced



(c) 3-layered sandwich samples without pillbox voids, as controls. These were made of 3 separate cured pieces, adhered together with the same resin. When viewed at an oblique angle these showed some unintentional thin imperfections at the layer interfaces.

(d) "Perfect" samples with potted-in brass button electrodes. This design was necessary for measurements on the silicone rubber materials. When perfect samples as in (a) had vapor-deposited aluminum electrodes applied to the silicone rubber materials, these electrodes were not conductive across the diameter of the electrodes. This was most likely due to the well-known problem of getting good adhesion to the silicone rubber. The potted-in brass button electrodes could be primed before the potting and then the silicone rubber adhered well.



a) Results of partial discharge testing of the Materials Samples:

Data tabulations of materials P.D. tests follow in Tables 5(a–d) through 8(a–f), as measured at various times during 1982–1983. The earlier data was taken with the borrowed 40 KV Biddle detector and ND 100 multichannel analyzer, later data with the new 60 KV Biddle equipment and ND 65 analyzer.

Some of the results are:

(1) The "perfect" Feldex R-6 samples begin to have P.D. pulses already at about 60 volts/mil or on the 0 to 5 KV ramp as compared to the Uralane and Conathane EN-11 samples which start much higher. The Feldex samples also show evidence of overstress at less than 400 volts/mil and fail after a few seconds at around 20 to 25 KV. The Uralane and Conathane can be taken to 40 KV or 1000 volts/mil and not fail. In the Feldex-R-6 samples the charge content of pulses is generally well below 100 pc, but there are a very large number of them, even at quiescent voltage. Small picocoulomb pulses are not harmless if there are enough of them. Howard [15] states that there is evidence that P.D.

*Table 5a. 1982 Data: Feldex R-6 S/N 13 "Perfect". Thickness = 40 mil.

VOLTAGE KV	TIME SEC	ΣN	1.5→25	26→50	51→100	101→150	151→200	201→250	251→300pc	Calibr: 1.5→300PC
0→2.5	10	2	2							
2.5	100	8	<22pc							
2.5→5	10	282		<37pc						
5	100	26	<22 + 34pc		2					
5→7.5	10	857	<38 + 46pc		2					
7.5	100	738	<25 + →50pc		1	1				
				5						
7.5→10	10	2108	<25 + →50pc		1	1				
				6						
10	100	3997	3976	21	1					
10→12.5	etc.	1260	←——1260——→							
12.5		492	484	7	1					
12.5→15		2147	2130	15	2					
15		106	99	7						
15→17.5		585	579	4	2					
17.5		552	540	11	1					7μa steady current
17.5→20										
20	(200)	12712	12677	39	9	1				
20→22.5		679	←——679——→							
22.5	(100)	4566	←——————→							
	(200)	6572								
	(250)	65858	←——————————————→							5.5μa steady current

*Explanation:
ΣN gives the total number of pulses in the calibration interval 1.5 to 300pc.
This is divided up into regions of charge where the pulses occur, eg. 1.5 to 25pc, 26 to 50pc, etc., etc.
Under these column headings the data is listed as either < 22 + 34pc, meaning "Most counts less than 22pc plus one at 34pc;
or : 3976 without a pc symbol behind it, meaning a pure number of counts."

Table 5b. 1982 Data: Feldex R-6 S/N 11 "Perfect". Thickness

VOLTAGE KV	TIME SEC	ΣN	1.5→25	26→50	51→100	101→150	151→200	201→250	251→300pc	Calibr: 1.5→300PC
0→5	10	3	< 4pc							
5	100	0								3μa steady current
5→10	10	9	< 6pc							
10	100	1								4μa steady current
10→15	10	80	<13pc							
15	100	337	<41pc							
		Some bursts - turn down								
Ground for 5 minutes. Up Again. *Same* polarity.										
0→5	10	0								
5	100	0								2μa steady current
5→10	etc.	2	< 9pc							
10		6	< 5 + 19 + 29pc							3.5μa steady
10→15		73	<23 + 31pc							
15		32	<16pc							4.5μa steady
15→17.5		31	<18 + 35pc							
17.5		56(1)	<14 + 30.32pc						+282 pc	4μa steady
TOTAL		142(2)		<32pc						
Ground for 5 minutes. Up again. *Reverse* polarity.										
0→5	10	0								
5	100	0								
5→10	etc.	5	< 3 + 11 + 29pc							
10		163		<31 + 38pc						3μa steady
10→15		1081								
15	5	3972	~3800	~100	28	5				

Table 5c. 1982 Data: Feldex R-6 S/N 38 Tiny Spherical Void (~20mil). Thickness = 40 mil.

VOLTAGE KV	TIME SEC	ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→2.5	10	5	<16pc		1					
2.5	100	10	< 8pc							
2.5→5	etc.	58	<16pc							
5		233	<22pc			10				
5→7.5		67	<17 +	28pc	1	2	2			4.3μa steady
7.5		962	<14 +	32pc			1	1		current
7.5→10		165	<16 +	28(3)pc						5.5μa
10		6771	<15 +	22→37pc				3		
				6						5.5μa
10→0	50	422	<14 +	20→35pc						
				5						

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Table 5d. 1982 Data: Feldex R-6 S/N 37 Tiny Spherical Void (~20mil). Thickness = 40 mil.

VOLTAGE KV	TIME SEC	ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5	10	205			3					
5	100	2002	1993	6			1			4.5μa current
5→7.5	etc.	2070	← 2056 →			6	8	1		4.5→3μa
7.5		158	← 156 →		2					
7.5→10		3388	← Accelarating discharges – turn down →							5μa

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Table 6a. 1982 and 1983 Data: "Perfect" Uralane 5753 LV S/N 8P Tray I

VOLTAGE KV	TIME SEC	ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5	10									
5	100									
5→10	etc.									
10										
10→15										
15										
15→20		1	1	at 18 KV						
20		69	<27pc	1						
20→25		25	<23pc	→ 41pc						
25		245(1)	211	34						
		416(2)	→	→41pc	1		1		1+?	
25→30		59		<30pc	1					
30		345(1)	→	→	<90pc	2				
		595(2)	→	→	→	3			1+?	
		769(3)	→	→	→	5			1+?	
30→0	50	4	<8pc		1					

Table 6b. 1982 and 1983 Data: "Perfect" Uralane 5753 LV S/N 7P Tray 1 (40 mil)

VOLTAGE KV	TIME SEC	ΣN	→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5	10									
5	100									
5→10	etc.									
10										
10→15										
15										
15→20		2	<4pc							
20		3	<5pc							
20→25		1	6pc							
25 TOTALS		67(1)	<20 pc	1			1			
		292(2)	124	5	2		1			
		632(3)	———→	65pc	1	3	1			
25→30		52	<14 + 23, 27pc							
30		333	327		6					
30→0	50	4	<5pc		1					

Table 6c. 1982 and 1983 Data: "Perfect" Uralane 5753 LV S/N 1 Tray II (40 mil)

VOLTAGE KV		TIME SEC	ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5		10	0								
5		100	0								
5→10		etc.	0								
10			0								
10→15			0								
15			12	<12 + 20pc							
15→20			9	<5pc							
20			17	<13pc							
20→25			13	<11pc							
25			45	34	3	7	1				
25→30			6	<17pc							
30	(1)	100	109	90	13	1	3	1	1		
	(2)	100	87	71	2	6	3	1	2		
	(3)	100	75	65	6						
								2	1	1	
	(4)	100	13	9	1		1				15→3000PC
									1	1	0 beyond 300pc
30→0		50	4	2	1	1					1.5→300PC

Table 6d: 1982 and 1983 Data: "Perfect" Uralane 5753 LV S/N 10 Tray I (40 mil)

VOLTAGE KV	TIME SEC	ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5	10									
5	100									
5→10	etc.									
10										
10→15										
15										
15→20										
20		96	<27pc							
20→25		28	<23 + 35pc							
25		238	←	→	87pc					
25→30		63	←		< 61 + 97pc					
30	100	535	←		→	112 + 142pc				
	200	997	"	"	"	"		+240pc		
TOTALS	300	1383	"	"	"	"		+240pc		

Table 6e: 1982 and 1983 Data: Uralane 5753 LV S/N 35 with Pilibox Void (t = ˙5 mil; void h = 43 mil, diam = 75 mil)

VOLTAGE KV	$\vec{E}$	TIME SEC	ΣN	1.5→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	Calibr: 1.5→300PC
0→5		10	0												
5	67	100	0												
5→10		etc.	6	<7 + 14 + 26pc											
10	133		7	<15pc			1								
10→15			30	<21pc	2	1									
15	200		10	<3 + 9, 10pc 19→25pc		2									
15→20			37	<25pc	4	2			1	2+					
20 (1)	266		19	<8pc	1	1	2		1						
(2)			38	<8pc	2	2	2		1	1					
Totals(3)			58	<10pc	4	4	1	1	3	1					
20		1200	109	———	———	101	———	———	———	———	———	———	——→	2	15→3000PC + 560, 580pc
												820, 1550, 2000, 2040pc			
		1200	107	———	———	105	———	———	———	———	———	———	——→		+ 600, 820pc
20→25			41	<20pc	5	1	3			1					1.5→300PC
25	300		39	<13pc	1	1	3		1	1					
25			46	←31	→	←	12	———	———	———	———	——→			15→3000PC + 580, 640, 1130pc
25→30			47	<26pc	1		3								1.5→300PC
30	400		39	<17 + 28pc		2	6	2	1	1					15→3000PC
30			29	←———	———	———	24	———	———	———	———	——→		1	+ 780, 840pc 900, 1620pc
30→0			16	←8	→	←	———	———	6	———	———	——→			+ 910, 1130pc

STARTS AT 6.5 KV = 86 $\frac{\text{VOLTS}}{\text{MIL}}$ Average Applied Field

Table 6f: 1982 and 1983 Data: Uralane 5753 LV S/N 34 with Pillbox Void (t = 96 mil; void h = 43 mil, void diam = 125 mil)

VOLTAGE KV	TIME SEC	ΣN1	5→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500pc	Calibr: 1.5→ 300PC
0→5	10													
5	100													
5→10	etc.	57	<10 + 22(2)pc				1		STARTS AT 6.4 KV					
			24, 25pc											
10		2	1, 5pc											
10→15		77	<15pc	1										
15		3	1, 6, 9pc											
15→20		59	51	7	1									
20		4	<4 + 19pc											
20→25		25	<11pc	3										
25		14(1)	<24pc	1	1									
Total		24(2)	<24pc	1	1		1							
25→30		45	<17pc	1	3									
30		25(1)	<25pc	4	1		1							
Totals		125(2)	<25pc	5	4	4	2							
		Bursts												
30		57(3)	<25pc	3	1	1								
Totals		132(4)	<25pc	12	3	2	3							15→ 3000PC
30		9(5)	7				1							+ 1670pc
Totals		28(6)	20		3		2						+ 1070, 1600, 1690pc	
		40(7)	29		4		2				+ 590, 1070, 1180, 1500, 1670pc			
30→35		7	<20pc		1						1			+ 2000pc
35		9(1)	<20pc			3		1					1	+ 1010, 2040pc
		24(2)		<40pc		4	3	1					1	+ 1010, 1750,pc 2040(2)pc
		37(3)		<50pc	3	←—	8	—→			510, 780, 1010, 1760, 1800, 2040(2)pc			
Totals		52(4)												
		67(5)												
		83(6)		<130 PEAK AT 80pc		←—	8	—→			500, 560, 710→ 1020, 1500→ 1840pc	4	6	
												+ 2050(2)		1.5→ 300PC
		64(1)	<21pc	2	1	1			1					
		115(2)	<22pc	2	1	1			3					
6.5μa Burst!		301(3)	←— 293 —→			3	2		3					
35→0		304	←→ <33pc		8			1	2					

Table 6g: 1982 and 1983 Data: Uralane 5753 LV S/N 36 with pillbox Void (t = 90 mil; void h = 41 mil, void diam = 125 mil)

VOLTAGE KV	TIME SEC	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500 pc	Calibr: 1.5→300PC
0→5	10													
5	100													
5→10	etc.	42	< 20 + 39(2) + 55pc											
10		5	< 2 + 30pc						STARTS AT 5.5 KV					
10→15		84	< 27pc		2									
15		7	< 10pc											
15→20		46	< 10	·, 20pc	1									
20		26(1)	< 10 + 17pc		2									
		40(2)	< 10 + 10→ 30pc		2									
		55(3)		< 30pc	2									
20		3(4)	10pc											15→ 3000PC
		6(5)	1	1	1									+ 540 + 2210pc
20→ 25		53	< 11→ 34pc		2	1			1				520,	540 + 2210pc 1.5→ 300PC
25		20	< 3pc	6										
		30	< 18pc	1										
25		8	< 20pc			1								15→ 3000PC
25→ 30		53	< 16pc	8									+	1180, 1370 + 2360pc
30		70(1)	< 12pc	2	2									1.5→300PC
		117(2)	< 24pc 5	3	2	1								
30		9(3)	< 20pc	1	1	2		1					1	15→ 3000PC + 630, 800, 850, 1050
		18(4)						1					1	630 +, 800, 550, 1050
30→ 0		391	←→	< 41pc	3	3		1						1.5→ 300PC

Table 6h: 1982 and 1983 Data: Uralane 5753 LV Empty cables in Fluorinert.

VOLTAGE KV	TIME SEC	ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5										
5										
5→10										
10										
10→15										
15										
15→20										
20										
20→25	10	6	<10pc	32pc						
25	100	8	<11pc	26pc						
25→30	10	7	<17pc	38pc						
30	100	15	<13pc	25, 27pc						
30	etc.	0								15→3000PC
										1.5→300PC
30→35		57	<25pc	5						
35		23	<18pc	4						
										15→3000PC
35		4		<50pc						
										1.5→300PC
35→0		6	<16pc		1					

Empty Biddle System

VOLTAGE KV	TIME SEC	ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr.
										1.5→300PC
25→30	10	2	<8pc							
30	100	9	<13pc	1						
30→35	etc.	12	<21pc		1					
35		9	<19pc	1						
35→0		3	<17pc			1				

Table 6i: 1982 and 1983 Data: Uralane 5753 LV S/N 50 Laminated (Flat defects of *unknown thickness* at laminated interfaces. *No* Pillbox Void. Spraypaint Electrodes).

VOLTAGE KV	ΣN 1.5→25		→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550pc	Calibr: 1.5→ 300PC
0→ 5														
5														
5→ 10	15	<15 pc					STARTS AT ~ 7.5 KV							
10	0													
10→ 15	28	<15 pc												
15	10	<7pc												
15→ 20	38	<15 + 25 pc												
20	27	<22 pc												
20														15→ 3000PC 1.5→ 300PC
20→ 25	36	<18+27pc	1		1									
25	42	<19 pc	2											
														15→ 3000PC
25	1			1										
25→ 30	10		<40pc			1								
30	4		3	1										
														1.5→ 300PC
30	78	<16 pc	2		1									
	123	<16 pc	4		1									
30→ 35	103	<25 pc	5	2		1								
35	126	<25 pc	6	6	3									
														15→ 3000PC
35	10	———	———	———	→									
														1.5→ 300PC
35→ 0	128	<24 pc				1								

Table 6j: 1982 and 1983 Data: Uralane 5753 LV S/N 51 Laminated (Flat defects of *unknown thickness* at laminated interfaces. *No* Pillbox Void. Spraypaint Electrodes).

VOLTAGE KV	ΣN	1.5→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500pc	Calibr. 1.5→300PC
0→5	0												
5	0												
5→10	8	◁10pc						STARTS AT ~ 7 KV					
10	2	◁11pc											
10→15	13	◁13pc											
15	4	◁14 + 28pc											
15→20	21	◁12pc											
20	32	< 25pc	4	3									
20→25	24	< 17pc											
25	15	< 21pc											
25→30	40		< 30pc										
30	57	< 19pc	1	2									
30	6		< 60pc										15→ 3000PC
30→35	45	< 25pc	2			1							1.5→ 300PC
35	82	< 25pc	3	3									
35	2	< 20pc											15→ 3000PC
35→0	86	< 27pc		1									1.5→ 300PC

Table 6k. 1982 and 1983 Data: Uralane 5753 LV S/N 122 "Imperfect" (Very lopsided plating with Pillbox Void.)

VOLTAGE KV	Calibr: PC	ΣN	3→25	26→50	51→100	101→150	150→200	201→250	251→300pc	
0	3→300	0								
0→10		6	6							
10		0								
10→20		17	15				1	1		
20		3	2				1			
20→25		5	3			1			1	
25		7	6		1					
25→30		9	8						1	
30	3→300	7	6						1	
30	30→3000	4	1	2			1			
30→35	"	5	1			1		1		+ 610, 1420pc
35	"	4			1	1				+ 330, 660pc
35	3→300	7				1				
35→40	30→3000	8	1	2		2				+ 330, 540, pc 650pc
40	"	8	←	4	→			1		+ 330, 460, 730pc
40	3→300	19	17			1		1		
40→0		48								

Table 6l: 1982 and 1983 Data: Uralane 5753 LV S/N 1181 "Imperfect" (With Pillbox Void)

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0	100	3→300								
0→10	~20		4	3				1		
10			0							
10→15			4	4						
15			0							
15→20			4	4						
20			0							
20→25			7	7						
25			0							
25→30			7	7						
30			4	3				1		
30→35			9	8	1					
35			16	15		1				
35→40			11	9		1				1
40			37	37						
40→0			62	56		2		2	1	1

Table 6m: 1982 and 1983 Data: Uralane 5753 LV S/N 1281 "Imperfect" (With Pillbox Void)

VOLTAGE KV	TIME SEC	CALIBR: pC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc	
0	100	3→300	0								
0→10	~20		13	10				1	1	1	
10	100		1	1							
10→20	~20		20	18						2	
20	100		9	8			1				
20→25	~20		6	5						1	
25			9	8					1		
25→30			13	9	2		1		1		
30			12	10				1		1	
30→35		30→3000	6			1		2			340, 420pc 490 pc
35		3→300	16	12	2	1			1		
35		30→3000	13	9		1					+ 380, 850pc 1100pc
35→40		"	6	1			2				+ 700, 730pc 790pc
40		"	17	← 13 pulses < 200 →							+ 340, 550pc 930, 1210pc
40		3→300	29	22		2	3	1	1		
40→0		"	172	164	4	2		1		1	

Table 6n: 1982 and 1983 Data: Uralane 5753 LV S/N 130P "Perfect"

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	250→300 pc
0	100	3→300	0							
0→10	~20		0							
10	100		0							
10→20	~20		0							
20	100		0							
20→25	~20		2	2						
25	100		0							
25→30	~20		1	1						
30			5	5						
30→35		30→3000	1	1						
35		"	0							
35		3→300	3	3						
35→40		30→3000	0							
40		"	0							
40		3→300	10	2	2	1				
40→0		"	10	7	2	1				

Table 6o. 1982 and 1983 Data: Uralane 5753 LV S/N 125P "Perfect"

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	250→300pc
0		3→300	0							
0→10			0							
10			0							
10→20			0							
20			0							
20→25			2	2						
25			0							
25→30			1		1					
30			2	1		1				
30→35			3	2	1					
35			8	7	1					
35→40			8	5	3					
40			14	11		2				
40→0			35	31	2	2				

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Table 6p. 1982 and 1983 Data: Uralane 5753 LV S/N 1331 Imperfect

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0			0							
0→10		3→300	10	9					1	
10			3	3						
10→20			19	14	2		1	1		1
20			3	2		1				
20→25			10	9					1	
25			3	1	2					
25→30			8	8						
30			7	6				1		
30→35			24	16	4			2	2	
35			15	14					1	
35→40			13	10	2	1				
40			12	8	3				1	
40→0			178	167	3	1	←	7 pulses	→	

Table 7a. 1982, 1983 Data: "Perfect" Conap EN-11 S/N 3P Tray I

VOLTAGE KV	ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5	0								
5	0								
5→10	3	<2pc							
10	0								
10→15	5	<2pc							
15	11		<30pc						
15→20	7		<32pc						
20	147(1)		<31 + 47pc	1					
	330(2)	————	———→	1	3				
20→25	24	<16pc	4	1					
25	569	————	————	————	————	———→	1	1	
	820	————	————	————	————	———→	1	1	
25→30	43	<20pc	2	1					
30	384	————	————	———→	4	3			
	614	————	————	———→	4	3			
	897	————	————	———→	4	3			
30→0	16	<15pc	2	1					

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Table 7b. 1982, 1983 Data: "Perfect" Conap EN-11 S/N 4P Tray 1

VOLTAGE KV		ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5										
5										
5→10		1	17pc				AT 7 KV			
10		15	<9 + 18pc	1	1					
10→15		2	<5pc							
15		4	<12pc							
15→20		6	<5pc		2					
20		538(1)	⟶	<33pc	2	1				
	Bursts	3960(2)	⟶	⟶	< 75pc	2	1			
		4002(3)	⟶	⟶	⟶	2	1			
20→25		20	<14pc							
25		498	⟶	⟶	<94pc					
25→30		35	⟶	⟶	<71pc					
30		222(1)	⟶	⟶	⟶	<110pc				
	Totals	460(2)	⟶	⟶	⟶	4	3			
		854(3)	⟶	⟶	⟶	7	4			
30→0		25	<17pc		1					

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Table 7c. 1982 Data: "Perfect" Conap EN-11 S/N 6P Tray I

VOLTAGE KV		ΣN	1.5→25	→50	→100	→150	→200	→250	→300pc	Calibr: 1.5→300PC
0→5										
5										
5→10		3	<2 + 18pc			STARTS AT 8.5 KV				
10		1	<2pc							
10→15		10	<5pc							
15		3	<4pc							
15→20		15	<4 + 11pc							
20		4	<6pc	1	1					
20→25		6	<7pc							
25		173(1)	→	→	4					
	Totals	365(2)	→	→	4					
25→30		23	<20pc							
30		302(1)		<32 + 47pc	1			1		
	Totals	659(2)	→	→<75pc	2	2		1		
30→0		18	<14pc	1						

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Table 7d. 1983 Data: Imperfect EN-11 S/N 112. 1
(T_t = .083"; Void = .041" and Diam = .075")

VOLTAGE KV	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0→10	3→300	2	1	1					
10		4	3	1					
10→15		4	4						
15		2	2						
15→20		10	9		1				
20		1	1						
20→25		15	12	1		1			1 +?
25		10	10						
25→30		17	14	1	1		1		
30		10	8	1					1 +?
30→35		17	16	1					
35		15	13	1					1 +?
3. →40		17	15	2					
40		21	21						

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Table 7e. 1983 Data: Imperfect EN-11 S/N 1161
($T_t \cong$ .060"; Void = .040" thick, .160 diam.)

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0→10	~20	3→300	12	12						
10	100		0							
10→20	20		13	10	1		1	1		
20	100		4	4						
20→25	10		10	7			2		1	
25	100		3	3						
25→30	10		10	9				1		
30			6	5		1				
30→35			12	7	1	2	1	1		
35			14	13						1 +?
35		30→3000	1				1			
35→40		3→300	13	8		3			1	1 +?
40		3→300	37	36				1		
40		30→3000	4	1			1			1 +320pc
40→0		3→300	25	22		1		2		

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Table 7f. 1983 Data: Empty System

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0		3→300	0							
0→20	~40		0							
20	100		0							
20→30	20		3		3					
30			2	2						
30→40			1			1				
40			1		1					
40→50			2	1			1			
50			0							

Table 7g. 1983 Data: Imperfect EN-11 S/N 1171
(T_t = 70 mil)

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0→10	~20	3→300	17	15	1			1		
10			0							
10→20			7	6						1 +?
20			1	1						
20→25			5	4	1					
25			0							
25→30			3	3						
30			4	3			1			
30→35			9	6	2					1 +?
35			18	18						
35→40			24	12	1	1				
40			102(!)	99	2		1			
40→0			45	41		1			2	1

Table 7h. 1983 Data: Imperfect EN-11 S/N 1191

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0→10		3→300	5	5						
10			1	1						
10→15			6	5					1	
15			2	2						
15→20			9	8						1 +?
20			1		1					
20→25			5	4	1					
25			7	7						
25→30			9	8					1	
30			18	14	4					
30→35			8	5		1			2	
35			38	36	2					
35→40			14	11		1		1	1	
40			46	36	3	2	1	3		1 +?
40→0			98(!)	88	4			1	2	3

Table 7i. 1983 Data: Perfect EN-11 S/N 120, 53% RH, 72° C

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0		3→300	0							
0→10			0							
10			0							
10→20			0							
20			0							
20→25			2	2						
25			0							
25→30			2		2					
30			3	3						
30→35			2		2					
35			5	5						
35→40			9	6	2	1				
40			45	45						

Table 7j. 1983 Data: Empty System (2nd time up)
56% RH. 77° F

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0		3→300	0							
0→20			0							
20			0							
20→30			3	3						
30			0							
30→40			2	1	1					
40			2	2						
40→50			3		2	1				
50			9	7			2			
50→60			15	11		2	1		1	
60			38	36	1					1
60→0			15	8	3	2	1		1	

Table 7k. 1983 Data: Imperfect EN-11 S/N 1231

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0	100	3→300	0							
0→10	~ 20		6	5	1					
10	100		1	1						
10→20	20		9	7	1					1
20	100		2	1						1
20→25	10		3	2					1	
25			1	1						
25→30			7	5	2					
30			5	4		1				
30→35			10	6		1			1	2
35			24	23		1				
35→40			6	3		2		1		
40			15	13	1				1	
40→0			57	36	5	1	3	←	12	→

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Table 71. 1983 Data: Empty System (2nd time up) 48% RH. 75° F.

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0		3→300	0							
0→10			0							
10			0							
10→20			0							
20			0							
20→30			1	1						
30			1	1						
30→40			2	1	1					
40			2	2						
40→50			2	1		1				
50			1		1					
50→60			2	1			1			
60			7	6		1				

Table 7m. 1983 Data: Imperfect EN-11 S/N 1241

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	1→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0			0							
0→10		3→300	6	5						1
10			2	2						
10→20			25	20		2		1	1	1
20			1			1				
20→25			12	8	2	1	1			
25			6	4	1		1			
25→30			22	17	4	1				
30			6	5	1					
30→35			21	15	2	1	2		1	
35			34	29		←	5	→		
35→40			28	18	3	3	2		1	1
40			22	17	3	1		1		
40→0			67	←	61 pulses	→			← 6 pulses	→

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Table 7n. 1983 Data: Imperfect EN-11 S/N 1311

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc	
0		3→300	0								
0→10			4	4							
10			1	1							
10→20			10	8	1		1				
20			2	2							
20→25			7	5	1					1	
25			7	5			2				
25→30			10	4	1	1	1	2	1		
30			16	12	1			2	1		
30→35			19	10	2	2	3		2		
35			43	30	2		3	2	4	2	
35		30→3000	13		1	4				4	+350, 430, 720, 1200pc
35→40			14	← 4 →		3	3				390, 540, 1230pc
40			27	← 17 →				1	1	3	+310, 510, 530, 610, 650pc
40		3→300	41	32	2		1	3	2	1	
40→0		"	36	30	4				1	1	

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Table 7o. 1983 Data: Perf ct EN-11, S/N 13?P

VOLTAGE KV	TIME SEC	CALIBR: PC	ΣN	3→25	26→50	51→100	101→150	151→200	201→250	251→300pc
0		3→300	0							
0→10			0							
10			0							
10→20			0							
20			0							
20→25			3	3						
25			3	3						
25→30			4	2	1				1	
30			2	2						
30→35		30→3000	0							
35		"	0							
35		3→300	11	11						
35→40		30→3000	0							
40		30→3000	2	1		1				
40		"	27	26					1	
40→0			12	11			1			

Table 8a. 1983 Data: Empty System with Clips and Cables | 1983 Data: DC 93-500, #91, Poured in Vacuum, Primed (¾" diam., .040" thick, cup) Tag on.

SEC	KV	ΣN	3→25	25→50	50→75	75→100	100→150pc	ΣN	3→25	25→50	50→75	75→100	100→150	150→200pc
100	0	0												
10	0→5	0												
100	5	0												
10	5→10	0						1	1					
100	10	0						0						
10	10→15	0						4	4					
	15	0						1	1					
	15→20	0						5	5					
	20	0						2	2					
	20→25	0						15	2			1		
	25	0						3	2			1		
	25→30	2	1	1				17	12	3	2			
	30	2	2					15	11	4				
	30→35	2	2					40	Continuous to 69pc			1		
	35	9	7	1	1			39	34	5	1			1
	35→40	5	5											
	40	41	41											
50	40→0	5	5					10	10					

Table 8b. 1982 Data: DC 93-500, #92, Poured in Vacuum Primed. (¾" diam., .040" thick, cup) Tag off. | 1982 Data: RTV 615, *as received*, #93, Poured in Vacuum Primed. (¾" diam., .040" thick, cup) Tag off.

SEC	KV	ΣN	3→25	25→50	50→75	75→100	100→150	150→200	ΣN	3→25	25→50	50→75	75→100	100→150	150→200pc
100	0	0							0						
10	0→5	0							0						
100	5	0							0						
10	5→10	0							0						
100	10	0							0						
10	10→15	0							0						
	15	0							0						
	15→20	2	2						4	3		1			
	20	6	6						2	2					
	20→25	5	5						8	7		1			
	25	8	8						3	3					
	25→30	7	7						23	20	2	1			
	30	7	7						3	3					
	30→35	12	12 →						18		3	2		1	
	35	29	26	2		1			23	19	2	2			
50	35→0	79	76	2	1				70	70					

Table 8c.

		1983 Data: RTV 615, *as received*, #94, Poured in Vacuum, Primed. (¾" diam., .040" thick, cup.) Tag off.							1983 Data: RTV 615, *DEVOL*, #96, Poured in Vacuum, Primed. (¾" diam., .040" thick, cup.) Tag off.						
SEC	KV	ΣN	3→25	25→50	50→75	75→100	100→150	150→200	ΣN	3→25	25→50	50→75	75→100	100→150	150→200pc
100	0	0							0						
10	0→5	0							0						
100	5	0							0						
10	5→10	2	2						0						
100	10	1	1						0						
10	10→15	3	3						0						
	15	0							0						
	15→20	6	6						2	2					
	20	0							0						
	20→25	7	5	2					5	5					
	25	12	11	1					0						
	25→30	14	9	3	2				10	7	2	1			
	30	6	5	1					0						
	30→35	29	21	5	2		1		16	8	5	2		1	
	35	28	25	3					4	4					
50	35→0	128	128						0	0					

Table 8d. 1983 Data: RTV 615, *DEVOL*, #95, Poured in Vacuum, Primed, (¾" diam., .040" thick, cup.) Tag off. | 1983 Data: RTV 615, *DEVOL*, #97, *no* Vacuum (Primed, Needle to Plane, cup.) Tag off.

SFC	KV	ΣN	3→25	25→50	50→75	75→100	100→150	150→200	ΣN	3→25	25→50	50→75	75→100	100→150	150→200pc
100	0	0							0						
10	0→5	0							0						
100	5	0							0						
10	5→10	0							2	2					
	10	0							0						
	10→15	2	2						6	5	1				
	15	0							0						
	15→20	4	4						8	7	1				
	20	0							4	4					
	20→25	6	6						16	16					
	25	0							7	7					
	25→30	10	7	3					31	30	1				
	30	2	2						17	15	1	1			
	30→35	8	5	2	1				52	48	1	3			
	35	3	2		1				35	28	6			1	
	35→0	3	2		1				2		1				1

RTV 615 straight out of the can somewhat worse.

No significant difference in partial discharge behavior between DC 93-500 and RTV 615 DEVOL.

Table 8e. 1983 Data: RTV 615, *DEVOL*, #88, *no vacuum*, *primed*, (needle to plane, cup). Tag off.

SEC	KV	ΣN	3→25	25→50	50→75	75→100	100→150	150→200pc
100	0	0						
10	0→5	0						
100	5	0						
10	5→10	0						
	10	0						
	10→15	2	2					
	15	0						
	15→20	2	1	1				
	20	0						
	20→25	6	5		1			
	25	1	1					
	25→30	12	10	1				
	30	5	5					
	30→35	23	21		2			
	35	8	8					
50	35→0	7	6	2				

Table 8f. 1983 Data: Vacuum potted in Blue cup

		#91, DC 93-500, Primed, (¾" diam., .040" thick) cup. 1→200pc		#95, Devolatal. RTV 615, Primed, (¾" diam., .040" thick) cup. 1→200pc	
		ΣN	Description	ΣN	Description
	0				
	0→5				
	5				
	5→10				
	10				
	10→15				
	15				
	15→20			3	<3pc
	20	8	<2pc + 7pc	33	<3pc
	20→25	16	<5pc	18	<4pc
	25	112	<8 + 12pc	92	<6pc
	25→30	64	<7 + 11,12,17,20pc	47	<7pc
	30	247	<9 + 11pc	184	<6pc
	30→35	73	<11pc	78	<7 + 11pc
	35	371	<11pc	360	<11pc
50	35→0	4	<3 + 16pc	11	<3pc + 8pc

pulses can do harm to insulation down to 0.2 pc if there are enough of them.

(2) Presumably because the average field strength is high in the plane parallel slab samples when pulses first appear, there are more discharges on the quiescent 100 second plateaus than on the 10 second ramps, even in the high resistivity Uralane. This is opposite from the big bulk FOC witness samples where the average field strength was weak even at the highest applied voltage of -17.5 KV, and discharges came from localized high fields at sharp corners and dielectric interfaces.

(3) Larger pc content pulses, that is above about 300 pc, are associated with larger voids. The Uralane and Conathane "Imperfects" with intentional pillbox voids began to show pulses with charge content between 500 to 2500 pc at average field strengths of about 250 volts/mil and above. These were definitely associated with the pillbox voids and were absent from all other samples, including the solid sandwich 3-layer samples without pill-box voids in the center layer. These latter ones did start having pulses at 80 volts/mil of less than 50 pc charge content, probably due to imperfections at the layer interfaces, but no discharges above 300 pc appeared all the way to field strengths of 1000 volts/mil. To recall, several thousand picocoulomb pulses were also seen in the front-end sample #3 of the FOC camera investigation. This sample had two large bubbles, the larger of approximate size 1.5 cm x 0.3 cm x 0.5 cm, trapped in the Feldex R-6 potting material. Thus several thousand picocoulomb charge content in single pulses appears to be characteristic of large voids. Table 9 and 10 illustrate this conclusion.

(4) Partial discharge behavior of silicone rubber "perfect" potting samples (cups) is also good up to 1000 volts/mil tested, with no significant difference evident between DC 93-500 and Devolatilized RTV 615. This was true both for the plane parallel and the needle to plane samples. The latter showed no evidence of growth of electrical trees after several hundred hours of Life test at 30 KV. Electrical treeing under DC applied voltage has only been seen by us in or on thin film insulation.

Table 9. Perfect vs. Imperfect Uralane

JUNE 8, 1983
PERFECT URALANE # 126P

VOLTAGE KV	TIME SEC	CALIBRATION PC	ΣN	3→25 PC	26→50 PC	51→100 PC	101→150 PC
0	100	3→300	0				
0→10	~20		0				
10	100		0				
10→20	~20		0				
20	100		0				
20→25	~10		2	2			
25	100		2	2			
25→30	~10		5	5			
30			5	4	1		
30→35		30→3000	0				
35		3→300	8	6	2		
35		30→3000	0				
35→40		30→3000	1		1		
40		30→3000	1				1
40		3→300	4	4			
40→0		3→300	9	5	2	1	

JUNE 8, 1983
IMPERFECT URALANE # 128I

VOLTAGE KV	TIME SEC	CALIBRATION PC	ΣN	3→25 PC	26→50 PC	51→100 PC	101→150 PC	151→200 PC	201→250 PC	251→300 PC	
0	100	3→300	0								
0→10	~20		13	10				1	1	1	
10	100		1	1							
10→20	~20		20	18						2	
20	100		9	8			1				
20→25	~10		6	5						1	
25			9	8					1		
25→30			13	9	2		1		1		
30			12					1		1	
30→35		30→3000	6			1		2			+340, 420, 490 PC
35		3→300	16	12	2	1			1		
35		30→3000	13	9		1					+380, 850, 1100 PC
35→40		30→3000	6	1			2				+700, 730, 790 PC
40		30→3000	17	←	13 PULSES			→			+340, 550, 930, 1210 PC
40		3→300	29	22		2	3	1	1		
40→0		3→300	172	164	4	2		1		1	

Table 10. Perfect versus Imperfect EN-11.

JUNE 15, 1983
PERFECT EN-11, # 132P

ELECTRODES 1.25" DIAM
0.040" THICK, 2.25 DIAM DISC

VOLTAGE KV	CALIBRATION PC	ΣN	3→25 PC	26→50 PC	51→100 PC	101→150 PC	151→200 PC	201→250 PC	251→300 PC
0	3→300	0							
0→10		0							
10		0							
16→20		0							
20		0							
20→15		3	3						
25		3	3						
25→30		4	2	1				1	
30		2	2						
30→35	30→3000	0							
35	3→300	0							
35	30→3000	11	11						
35→40	30→3000	0							
40	30→3000	2	1		1				
40	3→300	27	26					1	
40→0	3→300	12	11			1			

JUNE 15, 1983
IMPERFECT EN-11 # 1311

ELECTRODES 1.25" DIAM.,
2.25" DIAM, .080" THICK, .043" HIGH BY .075" DIAM. VOID

VOLTAGE KV	CALIBRATION PC	ΣN	3→25 PC	26→50 PC	51→100 PC	101→150 PC	151→200 PC	201→250 PC	251→300 PC	
0	3→300	0								
0→10		4	4							
10		1	1							
16→20		10	8			1				
20		2	2							
20→15		7	5						1	
25		7	5			2				
25→30		10	4		1	1	2	1		
30		16	12				2	1		
30→35		19	10		2	3		2		
35	3→300	43	30	2		3	2	4	2	
35	30→3000	13		1	4				4	+350, 430, 720, 1200 PC
35→40	30→3000	14		4	3	3		1		+390, 540, 1230 PC
40	30→3000	27		←17→			1	1	3	+310, 510, 530, 610, 650 PC
40	3→300	41	32	2		1	3	2	1	
40→0	3→300	36	30					1	1	

(5) Among the polyurethanes the EN-11 generally showed pulse inception at a somewhat lower voltage and a larger number of pulses than the Uralane 5753LV.

A very obvious conclusion is that "low" resistivity (10^{11} ohm-cm) resins such as Feldex R-6 are not suitable as high voltage potting compounds: they will be noisy (many partial discharges) and have low breakdown strength. Even as a layer in series with high resistivity insulation material, the use of such resins is questionable.

b) Life Testing of Material Samples

Some Life-testing of the same materials samples as in the previous section was accomplished concentrating mostly on the Urelane and the Conathane. The purpose was to see if there is a correlation between initial P.D. behavior and length of Life. Tables 11 and 12 give the participants and data of this test.

More of the same type of life testing needs to be done. But even from a limited study such as this some conclusions can be drawn:

(1) The Uralane "perfects" and "imperfects" appear to be more failure resistant from the electric stress point of view than the EN-11's. This is reasonable in that they are different polymers with different molecular make-up.

(2) It did appear that the EN-11 samples were more likely to vary from batch to batch than the Uralanes, in that both "perfect" EN-11's that failed came from an earlier batch. Standard polymer tests, however, detected no very significant differences in composition.

(3) Given the same material and geometry, there *is* a statistical correlation as seen in Table 12 between all the EN-11's that failed and their high sum of initial P.D.'s. This was summed on the ramps and voltage plateaus from data on the short-time initial ramp test profile, pulses being detected between 3 and 300 pc. It is seen in Table 12 that all the samples that had the sum $\Sigma n_i q_i$ in the several thousand picocoulombs failed, whereas the ones

Table 11. Preliminary Report on Life-testing of Material Samples

- PURPOSE: SELECT THE BETTER MATERIALS.

  IS THERE A CORRELATION BETWEEN INITIAL P.D. ACTIVITY AND LIFE?

- PARTICIPANTS: CONAP EN-11 URALANE 5753 LV

	CONAP EN-11		URALANE 5753 LV	
40KV SET I: 200 HRS + 30 TURN-ONS	3 PERFECTS 2 F'S	2 IMPERFECTS 2 F'S		2 IMPERFECTS 0 F'S
40 KV SET II: 260 HRS + 44 TURN-ONS	2 PERFECTS 0 F'S	3 IMPERFECTS 2 F'S	3 PERFECTS 0 F'S	3 IMPERFECTS 0 F'S

Table 12. Results on Life-tests Cont.

SETS I, II:

EN-11 PERFECTS	EN-11 IMPERFECTS	URALANE PERFECTS	URALANE IMPERFECTS
2/5 FAILURES	4/5 FAILURES	NONE/3	NONE/5

EN-11'S SAMPLE #	$\Sigma n_i q_i$ DURING INITIAL *SHORT-TERM* RAMP TEST TO 40 KV, CALIBR: 3→300 PC. RAMP + QUIESCENT	SURVIVED HOW LONG	PRESENT STATE
# 106 PERFECT	246 PC	30 TURN-ONS, 200 HRS	CONTINUES
# 117 IMPERFECT	2210 PC	1 TURN-ON, 7 HRS	FAILED ON ΔV
# 116 IMPERFECT	3150 PC	10 TURN-ONS, 49 HRS	FAILED AT 40 KV
# 119 IMPERFECT	3200 PC	4 TURN-ONS, 10.5 HRS	FAILED AT 40 KV
#112 IMPERFECT	2280 PC	1 TURN-ON, .08 HRS	FAILED ON ΔV
# 110 PERFECT	310 PC	44 TURN-ONS, 260 HRS	CONTINUES
# 120 PERFECT	670 PC	44 TURN-ONS, 260 HRS	CONTINUES
# 111 IMPERFECT	960 PC	44 TURN-ONS, 260 HRS	CONTINUES
# 104 PERFECT	660 PC	2 TURN-ONS, 16 HRS	FAILED ON ΔV

with much less P.D.'s did not fail. (The n_i = number of pulses at a given charge content q_i picocoulombs.) However, the correlation is seen to be statistical and not on a one on one individual basis. Individual variations in life test results are well known, [16, 17], as stated for example by G.C. Stone: "The time for breakdown of identical samples of a solid insulation tested at a fixed high voltage can vary over a range of 10:1.

(4) The importance of the sum of total charge transfer in corona degradation as an important quantity was pointed out by Burnham [18]. On our new ND 65 we now have the capability to calculate the sum $\Sigma n_i q_i$ immediately after each data acquisition, as will be seen below in the capacitor section, on some of the more recent measurements.

(5) Among the failures, 3 out of 5 occurred during the act of voltage turn-on, even though this was a very benign 10KV/5 second turn-on. For example, a test-object that sat without problem for 8 hours at 40 kv one day, failed during the next day's turn-on as the voltage passed the 30 kv mark. Failures during a turn-on after several months of satisfactory operation have occured in orbit.

(6) For a closer look at an individual samples' degradation, partial discharge testing should be interspersed during life testing to show progressive damage or, in other words, trend studies should be done. Table 13 shows sample #110 Perfect of EN-11 before and after 260 hours at 40 kv and 44 turn-ons.

c) Thermomechanical and Adhesion Considerations.

It must be remembered that the above Life-tests were carried out at very high average field strengths namely 1000 volts/mil. Electrically, both the EN-11 and the Uralane 5753 proved to be satisfactory, although the Uralane seemed somewhat better. The question arises as to what the *failure mode* of these polymers then really is under low or moderate D.C. electrical fields as in a flight high voltage assembly. The beginning of a problem could be due to thermomechanical and/or bad adhesion stresses which can start small cracks in the polymers. The thermal coefficients of expansion or contraction of the polymers are 20 times those of

Table 13. Trend Study

MAY 9, 1983
PERFECT EN-11 # 110P

CALIBRATION 3→300PC | MAY 27, 1983 REPEAT

VOLTAGE KV	TIME SEC	ΣN	3→25 PC	26→50 PC	51→100 PC	101→150 PC	ΣN	3→25 PC	26→50 PC	51→100 PC
0	100	0					0			
0→10	~20	0					0			
10	100	0					0			
10→20	~20	0					0			
20	100	0					0			
20→25	~10	5	5				2	2		
25	100	1	1				3	3		
25→30	~10	1			1		1		1	
30		0					1	1		
30→35		3	1	1	1		2	1	1	
35		1	1				1	1		
35→40		1			1		1		1	
40		6	6				1	1		
40→45		2	1			1	3	2		1
45		24	23			1	14	11	3	
45→50		4	3		1		4	1	2	1
50		49	48	1			11	8	1	2

SEPT 8, 1983 AFTER LIFETEST
AT 40KV, OF 260 HRS & 44 TURN-ONS

VOLTAGE KV	TIME SEC	ΣN	3→25 PC	26→50 PC	51→100 PC	101→150 PC	151→200 PC	201→250 PC	251→300 PC
0	100	0							
0→10	~20	0							
10	100	0							
10→20	~20	8	8						
20	100	0							
20→25	~10	1		1					
25	100	4	4						
25→30	~10	1		1					
30		2	2						
30→35		3	2	1					
35		18	18						
35→40		11	10	1					
40		40	38		1		1		
40→45		9	5	1	2	1			
45		51	46	2	2		1		
45→50		17	13	2	1		1		
50		237	226	7	1	2		1	

the inorganic circuit components embedded within them. Small cracks once begun, will grow with relatively small stress subsequently. The partial discharges within these cracks also serve to enlarge them further, this being a much faster process on A.C. applied voltage however than on D.C. Finally this leads to an electrode to electrode catastrophic breakdown. Knowledge of adhesive properties and of tear strength and crack propagation speed is therefore as important to the proper choice of potting materials as electrical properties. To this end

(1) we are enclosing some adhesion data measured during the past few years. Table 14.

(2) we point out important Materials work presently being done at G.E.'s Space Technology Center and elsewhere on elastic, thermomechanical and cracking properties [19, 20]. It appears that Uralane cracks grow faster than cracks in DC 93-500.

(3) we have begun thermal shock cycles on small cups filled with the different resins, a heavy stell hexnut having been buried in each resin cup. Soft X-rays from a Lixiscope and power supply by Dr. Lo I. Yin and Mr. Arthur Ruitberg respectively will serve to reveal cracking in the opaque resins.

(4) Thermomechanical stress analysis should be carried out when potting designs are planned. The less confinement of a potting mass the less the mechanical stresses will finally be. Freedom to expand or contract must be given to the polymer, and temperature excursions, both during cure and during service of the cured polymer should be minimized.

Other possible potting materials than in this study have been evaluated for high voltage in Space use by other authors [21, 22, 23]. The ones named below fulfill a criterion of low viscosity at ambient temperature needed for impregnating miniwound high voltage transformer coils. These, generally, then require a higher cure temperature (more than 50°C). Conap EN-2521, Stycast 2651, 3M EC 2216, RTV 615 are such low viscosity resins. Work with one or another of these to impregnate coils for high voltage transformers and explore P.D. testing techniques, both D.C. and A.C., is planned by us for the near future.

Table 14. Adhesion Test Results.

I. Lap Shear Strength of Shell Epon 828/Miller Stephenson V-40. (Each average is based on six samples.)

(A) Adherent: 60% tin 40% lead solder, electro-plated on Beryllium Copper.

Adhesive Thickness: 0.019 inches ± .002

Surface Treatment	*Standard Deviation psi*	*Average Strength psi*
As received	± 100	700
200-proof Ethanol spray	± 80	900
Ultrasonic clean, with Freon TF	± 230	1000
Ultrasonic clean Freon, paper towel rub, ultrasonic clean	± 250	1180
Vapor degrease Trichloroethane, 74°C.	± 260	1170
Vapor degrease Trichloroethylene, 84°C.	± 240	1220
Ethanol sprayed, SiC 320 paper by hand, Ethanol sprayed	± 50	1200
Ultrasonic clean "sand blasted" with glass balls, ultrasonic clean Freon TF	± 210	1360
Trichloroethylene vapor degreased, "sand blasted" with glass balls, vapor degreased	± 230	1810
Ultrasonic clean Freon, "sand blasted" with Black Beauty grit, ultrasonically cleaned	± 120	1950

(B) Adherent: Glass Epoxy Board

Adhesive Thickness: 0.019 inches ± .002

Surface Treatment	*Standard Deviation psi*	*Average Strength psi*
Vapor Degrease with Trichloroethylene	± 240	1350
Ultrasonic clean, Freon TF	± 200	1900

Surface Treatment	Standard Deviation psi	Average Strength psi
200-proof Ethanol Spray	± 260	2000
Vapor degrease with trichloroethylene, sand blast with glass balls, vapor degrease	± 80	1380
Ultrasonic clean Freon TF, sand blast with glass balls, ultrasonic clean	± 240	1430

(C) *Adherent:* Porcelain

Adhesive Thickness: 0.019 inches ± .002

Scrubbed with Bon Ami, rinsed with distilled water, dried, vapor degreased trichloroethane > 1400

Porcelain broke on all samples before adhesion failure.

(D) *Adherent:* Ferrite

Adhesive Thickness: 0.019 inches ± .002

Ultrasonic clean with Freon TF > 1150

Ferrite broke on all samples before adhesion failure.

II. Variation of Lap Shear Strength with Glue Line Thickness

Adhesive: Epon 828/Miller Stephenson V-40

Adherent: Glass Epoxy Board

Thickness of Glue Line Inches	Standard Deviation psi	Lap Shear Strength psi
.008"	± 300	2450
.019"	± 100	1900
.030"	± 290	1710

Adherent: 60-40 Solder on Beryllium Copper

Surface Prep: Ultrasonic clean, Black Beauty Grit, Ultrasonic clean

.010"	± 50	2100
.019"	± 120	1950

Adherent: 60-40 Solder on Beryllium Copper

Surface Prep: Ultrasonic, Paper Towel Rub, Ultrasonic clean

.010"	± 100	1460
.019"	± 250	1180

III: Lap Shear Strength of Sylgard 184. Primed with Sylgard Primer.

(A) Adherent: Solder

Adhesive Thickness: 0.010 inches ± .002

Surface Treatment	*Standard Deviation psi*	*Lap Shear Strength psi*
Vapor degreased Trichlorethane, primed with Sylgard primer	± 75	320
Vapor degreased Trichloroethane, grit blast Black Beauty, vapor degreased again, primed	± 60	495
Same as above, 0.020" glue line	± 35	470

(B) Adherent: Glass Epoxy Board

Adhesive Thickness: 0.010 ± .002

Surface Treatment	*Standard Deviation psi*	*Lap Shear Strength psi*
Vapor degreased Trichloroethane, primed Sylgard primer	± 45	315
Same as above and grit blasted Black Beauty grit	± 20	565

IV: Lap Shear Strength of Thiokol Solithane 113, Formulation 4: 100 gm resin, 100 gm hardener.

(A) Adherent: 60-40 Solder, Electro-plated on Beryllium Copper

Adhesive Thickness: 0.010 inches ± .002

Surface Treatment	*Standard Deviation psi*	*Lap Shear Strength psi*
Ultrasonic Clean with Freon TF	± 25	90
Vapor Degrease Trichloroethane	± 15	95

Surface Treatment	Standard Deviation	Lap Shear Strength psi
Alcohol Spray	± 5	110
Vapor degrease with Trichloroethane, sand blast with Black Beauty grit, vapor degrease	± 15	160
Vapor degrease with Trichloroethane, prime with thin coat of Epon 828/V-40. Primer used	± 65	355

(B) Adherent: Glass Epoxy Board

Adhesive Thickness: 0.010 inches ± .002

Surface Treatment	Standard Deviation	Lap Shear Strength psi
Vapor degrease with Trichloroethane, grit blast Black Beauty grit, vapor degrease	± 30	215
Vapor degrease with Trichloroethane	± 40	220

(C) Adherent: Ferrite

Adhesive Thickness: 0.010 inches ± .002

Surface Treatment	Standard Deviation	Lap Shear Strength psi
Ultrasonic clean, hand sanded on 400 grit SiC paper. Ultrasonic clean with Freon TF (Johnson)	± 15	60
Repeat above (Clatterbuck)	± 20	60
Ultrasonic clean only	± 20	100

(D) Adherent: Porcelain

Adhesive Thickness: 0.010 inches ± .002

Data very poor despite many tries. Perhaps the heavy cutting grease from the daimond saw is never quite removable.

Surface Treatment	Standard Deviation	Lap Shear Strength psi
Vapor degreased, Trichloroethane	± 30	30
Vapor degreased, Trichloroethane, Bon Ami scrubbed, washed, dried, vapor degreased	± 65	75

Surface Treatment	*Standard Deviation*	*Lap Shear Strength psi*
Ultrasonic clean Freon, Bon Ami scrubbed, washed, dried, ultrasonic clean Freon	± 50	80

V: Lap Shear Strength of Thiokol Solithane, Formulation #11

Thiokol C113 Resin: 100g, C113-300 hardner: 44g, TIPA: 6g.
All samples ultrasonically cleaned with Freon-TF.

	Adherent Surface Treatment	*Adhesive Thickness Inches*	*Standard Deviation psi*	*Lap Shear Strength psi*
I.	No primer used: 60-40 Solder on Be-Cu	0.010	± 96	576
II.	Chemlock 218 Primer: Thinned 50%-50% with MIBK			
	60-40 Solder on Be-Cu	0.010	± 152	850
	Sandblasted Glass Balls, 60-40 Solder on Be-Cu	0.010	± 195	1070
	Porcelain	0.010	± 88	416
	Etched Teflon	0.010	± 23	292
III.	Epon 828 Epoxy Primer: Thinned 50%-50% with Methyl Alcohol			
	Etched Teflon	0.010	± 12	365
		0.020	± 10	360
	Porcelain	0.020	± 45	590
	60-40 Solder on Be-Cu	0.010	± 70	780
	Sandblasted 60-40 Solder on Be-Cu	0.010	± 130	860

VI: Lap Shear Strength of Thiokol Solithane #6

Thiokol C113 Resin 100g, Thiokol C113-300 hardner 120g. All samples were ultrasonically cleaned with Freon TF.

Adherent: 60-40 Solder, Plated on Beryllium Copper.

Adherent Surface Treatment	*Adhesive Thickness Inches*	*Standard Deviation psi*	*Lap Shear Strength psi*
Woolsey Metalast 919/920	0.020	± 20	130 Cohesive Failure
Woolsey Metalast	0.010	± 28	165 Cohesive Failure
Adherent: Etched Teflon			
Woolsey Metalast 919/920 Primer	0.020	± 4	132 Cohesive Failure
Woolsey Metalast 919/920 Primer	0.010	± 10	131 Cohesive Failure
Adherent: Sandblasted Glass-Epoxy Board			
Woolsey Metalast 919/920	0.020	± 14	81 Cohesive Failure
Woolsey Metalast 919/920 Primer	0.010	± 15	151 Cohesive Failure

VII: FOC Adhesion Lap Shear Tests (Courtesy C. Clatterbuck, Code 313, GSFC) 3 Samples of Each Variation.

Adhesive Between Substrate Coupons	Lap Shear Adhesive Strength psi	Average psi
Kovar to Kovar Substrate		
Uralane 5753 LV, no primer	155 108	132
Uralane + PR-1 primer	397 734 424	517
Uralane + PR-1 + upraded the Kovar substrate with 320 A10 paper	424 346 361	377
Scotchweld 2216, filled with 60% silver flakes by weight	651 618 565	611

Adhesive Between Substrate Coupons	Lap Shear Adhesive Strength psi	Average psi
Scotchweld 2216, filled with 80% silver flakes by weight	543 536 563	547
Epon 828/Versamid 140, filled with 15% conductive carbon by weight	520 484 625	543
Stycast 3050 with 5% Cabosil by weight	766 526 878	723
<u>Glass to Glass Substrate</u>		
Uralane 5753 LV, no primer	212 284 186	227
Uralane + PR-1 primer	528 321 493	447
Scotchweld 2216 with 60% silver flakes by weight	891 577 1113	860
Scotchweld 2216 with 80% silver flakes by weight	282 253 418	318
Epon 828/Versamid 140, filled with 15% conductive carbon by weight	341 497 184	341
Stycast 3050 with 5% cabosil by weight	896 885 734	832
DC-93-500 Silicone rubber with Q3-6060 primer	655 582 450	562

IV. Capacitor D.C. Partial Discharge Data, and Life Tests

a) Summary of earlier work

Much work has been done by us during the last several years on D.C. partial discharge measurements of commercially available high voltage capacitors. This has revealed great differences in both numbers and charge content of pulses among different kinds of high voltage capacitors suitable for electronic high voltage power supplies for Space flight. As a summary Table 15 shows some typical D.C. P.D. behavior. Even the same type such as solid ceramic disc barium titanate capacitors by different manufacturers vary greatly between the manufacturers.

Some salient points illustrated by Table 15 are: First, many more pulses and hence information as to the presence of discharge sites inside the capacitors appears on the 10 second ramps in these devices of low $\partial/\epsilon\&_o$ than on the 100 second quiescent plateaus (∂ = conductivity, ϵ = relative permittivity or dielectric constant, $\&_o$ = permittivity of empty space). Second, inception of discharges is considerably below the rated voltage stated by the manufacturer. Electronics designers are perhaps not aware that they are using the high voltage D.C. capacitors at voltages where partial discharges indeed occur. To obtain length of service estimates, one must additionally do Life testing, interspersed with D.C. P.D. tests which should give trend data. An earlier study of this type for single disc ceramic capacitors has been published elsewhere by us [12]. This earlier study was carried out for 1000 hours at 85°C and at constant D.C. voltage of 1.5 times rated. It showed that the several batches of capacitors with high amounts of initial P.D.'s did not necessarily all fail on Life testing, but the ones that did fail all came from high initial P.D. batches.

Table 15. D.C. Partial Discharge Histograms of various Types of D C. High Voltage Commercial Capacitors.

Applied dc volts	Micapaper Spiral Wrap, Impregnated, Flat; S/N 19; 10,000 pf; 8000 v rated; Calibration: 3 - 600 pc		Mylar spiral Wrap, Flat, Encapsulated; S/N 13; 10,000 pf; 6300 v rated; Calibration: 30 - 6000 pc	
KV	ΣN	Description	N	Description
0	0		0	
0 - 2	0		167	Most < 570+852,945,1832 pc
2	0		3	6 pc
2 - 4	4	Most < 5 pc	882	Most < 1151 + 15 pulses to 3053 pc
4	0		24	Most < 39 + 61 pc
4 - 6	8	Most < 34 pc	1333	Maxwellian continuous to 5424 pc
6	0		21	Most < 17 pc
6 - 8	14	Most < 19 + 66 pc		
8	1	6 pc		
	AC CIV:	2200 v rms	AC CIV:	275 volts rms

Solid Ceramic Disc, Manuf. A; 1000 pf; 10,000 v rated; Calibration: 2 - 400 pc			Solid Ceramic Disc, Manufacturer C; 1000 pf, 4000 v rated; Calibration: 2 - 460 pc			Stacked Ceramic MultiLayer; 1000 pf, 5000 v rated; Calibration: 10 - 3000 pc		
Appl. KV	ΣN	Description	Appl. KV	ΣN	Description	Appl. KV	ΣN	Description
0	0							
0 - 5	3	Most < 4.5 pc	0	0		0	0	
5	7	Most < 7 pc	0 - 2	21	Most < 400 pc	0 - 1.25	8	Most < 71 pc
5 - 10	9	Most < 10.6 pc	2	1	2.8 pc	1.25	0	
10	3	Most < 6.6 pc	2 - 4	203	Maxwellian continuous to 460 pc +?	1.25 - 2.5	64	Most < 317 + 423 pc
						2.5	0	
AC CIV: 4500 v rms			4	10	Most < 54 +215+282 pc	2.5 - 3.75	206	Most < 306 +405,413,425 452,590,599(2),1148, 1585 pc
						3.75	0	
						3.75 - 5	172	Most <1104+ 8 pulses to 2011 pc
						5	1	44 pc

Considerable and prolonged experience was also obtained with thin film capacitors: Mylar spiral wrap, cylindrical, hollow, airfilled, 10,000pf, 8 KV; Mylar spiral wrap, flat, airfilled, encapsulated, *not* impregnated, 10,000pf, 8 KV. Results were

(1) As can already be seen in Table 15, these have enormous amounts of corona or partial discharge on ramping to rated voltage. Without reproducing all the details, two sets of data suffice to show contrast to solid reconstituted, resin-impregnated mica capacitors:

	Tubular, hollow #12 Mylar Spiral Wrap 10,000pf, *8000 v rated* Calibrat: 30→6000pc		Impregnated, Solid, Micapaper Spiral Wrap 10,000pf, *8000 v rated* Calibrat: 3→600pc	
Applied D.C. volts:	ΣN	Description	ΣN	Description
0	0		0	
0→2KV	26	Most <100pc +311pc	0	
2KV	0		0	
2→4KV	303	Most <593pc	4	Most <5pc
4KV	8	Most <83pc	0	
4→6KV	972	Most <1186 + 1427, 1667, 2296pc	8	Most <34pc
6KV	3	10, 20, 417pc	0	
6→8KV	1443	Most <1691pc + 11 pulses to 3686pc	14	<19 + 66pc
8KV	3	Most <141pc	1	6pc

A.C. Corona Inc. V: 1000 V rms.   A.C. Inc. V. 2200 V rms.

Mylar spiral wrap, hollow, airfilled:

10,000 pf, 8 KV rated   0→8KV total ramp $\Sigma n_i q_i$ = 537 [illegible]0pc

Mica spiral wrap, solid, resin impregnated:

10,000 pf, 8 KV rated   0→8KV total ramp $\Sigma n_i q_i$ = 434pc

The above is measured in ambient air, and after having the aluminum print electrodes on the Mylar "cleared" or evaporated at punctures through the film or at flash-overs. This corona is to be expected since the aluminum print pattern is surrounded by gas and the edges of the print are sharp and electric fields are high there. The capacitor survives this corona for very long due to the self-clearing feature, and due to the added reliability derived from the electrode print pattern being several condensors in series within the single capacitor piece of hardware; but some treeing damages has been seen upon dissection.

(2) After time in vacuum, there are reduced pressures *inside* the hollow capacitors. We have found that in about 20% of parts, end to end total discharges develop. This is due to careless construction of the end electrodes: Whenever there is an unobstructed, gaseous, low pressure path from metal at one end cap to metal at the other end cap the internal arcs will happen at certain reduced pressures according to Paschen's curves. These internal arcs happen several times/minute for a while, then stop, then start again after a half hour or so. The capacitor survives this for a long time, but the voltage output has large transients on it, of course. Initial vacuum bake-out at 70°C appears to help to prevent the internal arcing in vacuum.

(3) A third phenomenon, not at all understood, also occured in vacuum:

A few of these capacitors arced from the *outside* negative terminal to ground at good vacuum, at a frequency of one or two times per week. Again, the capacitors survived, but secondary arcs accompanying the outside arc from the capacitors destroyed diodes, IC's, transistors in low voltage parts of the circuit.

In short, whereas such thin-film, hollow capacitors might be all right in atmospheric pressure uses, they are not suitable for use in the vacuum of Space. Solid capacitors, such as resin-impregnated, reconstituted mica and properly selected ceramic capacitors must be used. The resin-impregnated mica capacitors have a very small amount of partial discharge on ramping to rated voltage, as seen in Table 15.

Some of the most recent capacitor work follows:

b) 5-disc back-to-back ceramic capacitor module

Manufacturer H's ceramic ($BaTiO_3$) 5-disc back-to-back capacitor modules were P.D.

tested to compare them to 5-unit capacitor modules of reconstituted, resin-impregnated mica by manufacturer U. Neither type here was totally satisfactory in that

(1) H's modules showed problems with the two outermost capacitors at each end. These exhibited a run-away corona at only 20% above rated voltage on the quiescent plateau. In fact, after turning the applied voltage down and then up again to only $\frac{1}{2}V_R$, the end capacitors now showed the clearest symptom of damage, namely preferred peaks of charge content of pulses on the P.D. histograms. This indicates localized concentrations of discharges that would very quickly lead to catastrophic failure. Figure 12 shows reproductions of a preferred peak histogram and also of the more usual quasi-Maxwellian distribution type of histogram.

(2) In the reconstituted mica module by manufacturer U the capacitors were almost discharge-free on the voltage plateau which is good. However, on the voltage ramps above $\frac{3}{4}V_R$ there were several discharges in the 1000pc range which usually indicates some large voids.

The outcome of this study was that manufacturer H corrected the end terminations, and the new modules will be tested again.

Tables 16a through 17d gives the original data, as well as Figures 13 and 14.

c) Multilayer ceramic ($BaTiO_3$) capacitor (manufacturer K.) investigation

Due to their volumetric "efficiency", meaning small size, multilayer ceramic capacitors in the voltage range to 5 KV D.C., have recently begun to appeal to designers of high voltage power supplies. Some P.D. investigations were done on 10,000pf, 5 KV rated multilayers to see first of all whether the D.C. ramp test could distinguish between samples that had small cracks as revealed by the ultrasonic SLAM tests and those that had no cracks. Indeed the voltage at which the first few counts appeared upon ramping was at 1.9 and 2.0 KV for the cracked ones versus 2.3 and 2.8 KV for the ones with no cracks. Also the number of pulses on the 1.25 to 2.5 KV ramp was more for the cracked ones than the intact samples. How-

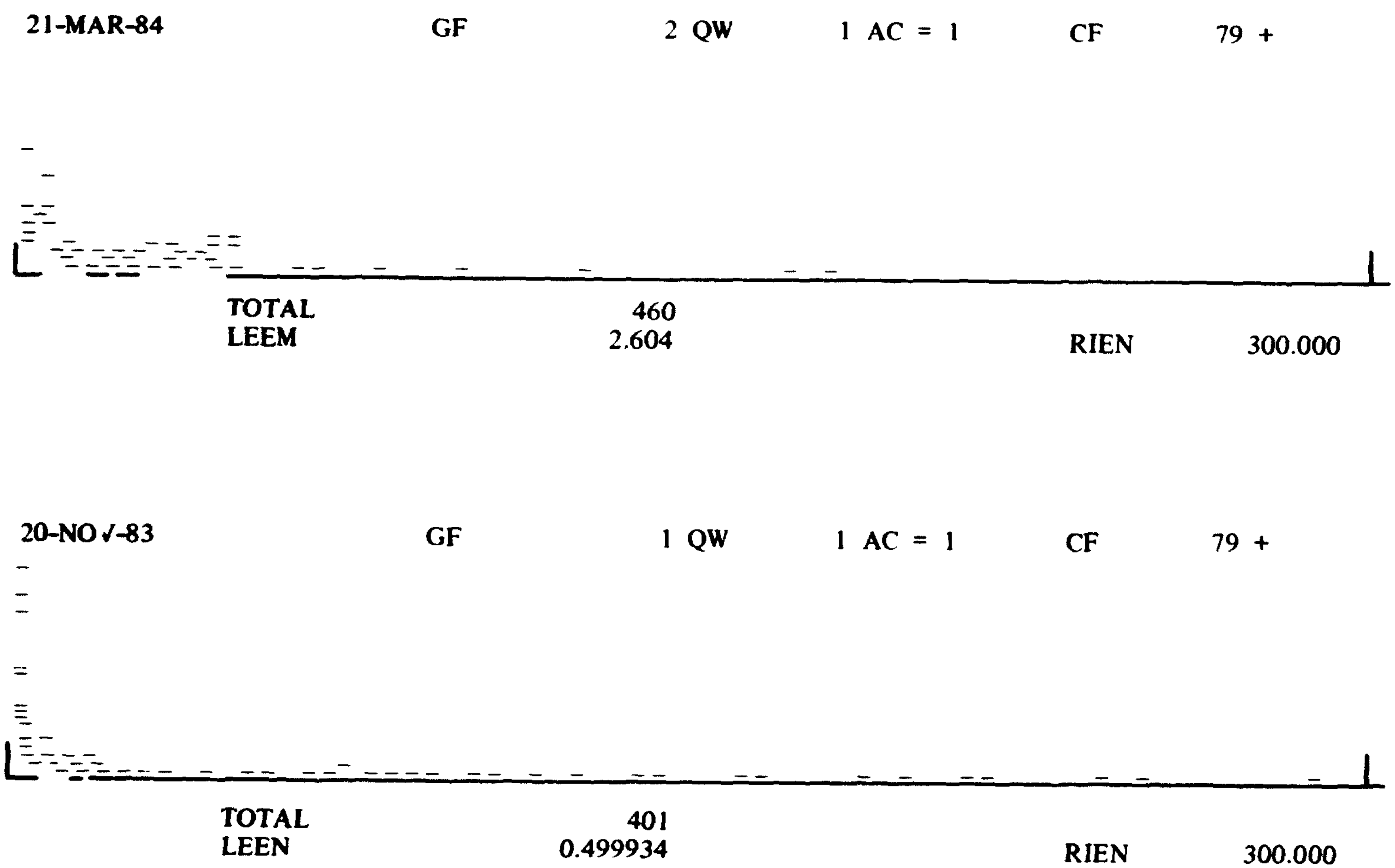
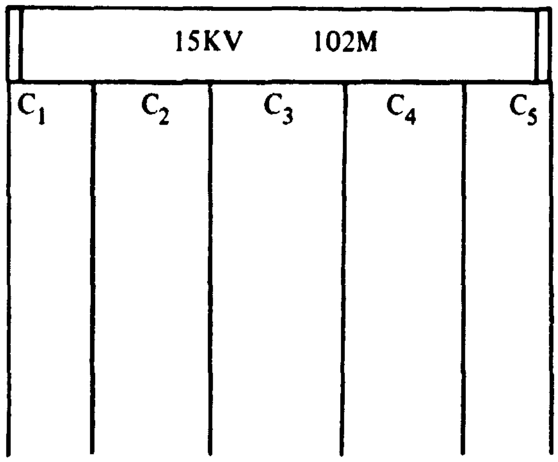


Figure 12. *Above:* "Preferred-peak" distribution. *Below:* Ordinary distribution.

Table 16a. Manufacturer H: 5 Capacitor Module. (Each 1000pf, 15 KV)



ECD
Capacitance
Meter
Model 100

C_1 = 835 ± 5pf (850)

C_2 = 930 ± 5pf (940)

C_3 = 975 ± 5pf (990)

C_4 = 920 ± 5pf (940)

C_5 = 870 ± 5pf (865)

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Table 16b. Manufacturer H: 5 Capacitor Module. (Each 1000pf, 15KV)

C_1		2.6→300pc								$\Sigma n_i q_i$
KV	ΣN	2.6→25	→50	→75	→100	→125	→150	→175pc		Σpc
0→3.75 (~15sec)	0									
3.75 (100sec)	0									
			Starts at ~4.5KV							
3.75→7.5	70	46	11	6	2	3	1		+149pc	Σ2051
7.5	39	33	4	1					+119pc	Σ583
				26→3000pc						
		26→250pc								
7.5→11.25	8	7							+265pc	Σ(642)
				2.6→300pc						
11.25	30	27	3							Σ388
11.25→15	229	192	24	5	2	1	0	2	+214, +283pc +?	Σ4151
15	63	58	4						+52pc	Σ685
				26→3000pc						
15→18.75	229!	214	9	3	1(961pc)				+1180, 2976pc peak at 180pc	Σ29,871
				2.6→300pc						
18.75 (80sec)	Bursts! 2803	2202	345	115	53 12	22 15	12 6	5 10	+301pc +306pc +? peak at 86pc	Σ60,670

Up Again: KV	ΣN	2.6→25	→50	→75	→200	→225	→250	→275pc		
0→3.75	0									
3.75	0									
3.75→7.5	102	78	14	2	1		4	3	+289pc +?	Σ3,537
7.5	368	120	89	103	8	2	7	11		Σ21,305

DAMAGED.

Table 16c. Manufacturer H: 5 Capacitor Module. (Each 1000pf, 15KV)

KV	ΣN	2.6→25	→50	→75	→100	→150	→175pc		Σpc
C_2				2.6→300pc					
0→3.75	0								
3.75	0								
				Starts at ~6KV					
3.75→7.5	9	5	1	1	2				Σ301
7.5	2	2							Σ15.2
7.5→11.25	30	25	2	3					Σ518
11.5	18	18							Σ109
11.25→15	95	76	13	2	0	1	2	+295pc	Σ1896
15	90	88	2						Σ559
				26→3000pc					
15→18.75	2!	37.9	76.9						Σ114.8
				2.6→300pc					
18.75	198	191	7						Σ1476
18.75→0	24	22	2						Σ221
C_3				2.6→300pc					
0→3.75	0								
3.75	0								
				Starts at ~4KV					
3.75→7.75	58	36	9	1	4	6	1	+163pc	Σ2009
7.5	16	16							Σ86
7.5→11.25	70	52	10	3	3	2			Σ1465
11.25	63	63							Σ247
11.25→15	148	131	8	6	3			peaks at22pc	Σ2001
15	252	252	1						Σ1662
				26→3000pc					
15→18.75	7!	7	(to 121.9pc)						Σ(487)
				2.6→300pc					
18.75 615	615	608	7					peaks at 17.8pc	Σ4738
18.75→0	73	46	13	5	5	3			Σ1975

Table 16d. Manufacturer II. 5 Capacitor Module. (Each 1000pf, 15KV)

C_4

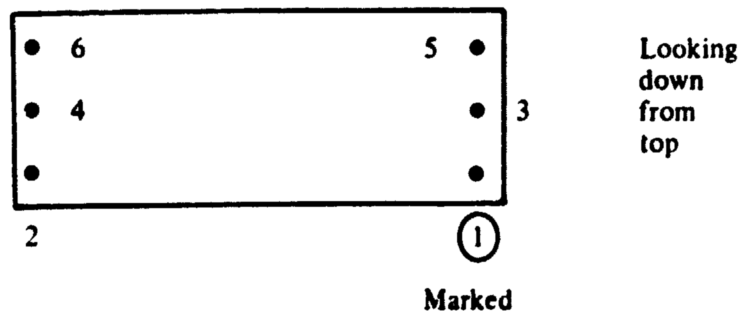
2.6→300pc

KV	ΣN	2.6→25	→50	→75	→100	→125	→150	→175pc		Σpc
0→3.75	0									
3.75	0									
				Starts at 5KV						
3.75→7.5	23	12	6			2	2		+200pc	Σ1083
7.5	2	2								Σ8
7.5→11.25	59	46	7	1	1	3			+204pc	Σ1374
11.25	33	33								Σ222
11.25→15	145	132	6	2	3		1		+302pc +?	Σ2075
15	217	208	3	5					+76.6pc	Σ2044
15→18.75	276	263	7	5					+106pc	Σ2880
18.75	671	643	17	11						Σ6291
18.75→0	57	37	10	6	3				+100.6pc	Σ1421

C_5

KV	ΣN	2.6→25	→50	→75	→100	→125	→150	→175pc		Σpc
0→3.75	0									
3.75	0									
				Starts at ~7KV						
3.75→7.5	2									Σ12.7
7.5	10	8								Σ147
7.5→11.25	116	102	10	2	1				+100.6pc	Σ1631
11.25	85	79	4	1						Σ996
11.25→15	277	229	27	9	5	2	3	1	+203pc	Σ4944
15	564	538	16	6	2	1			+135pc	Σ5795
Down Again										
Up Again										
15	520	484	23	10	2				+81.7pc	Σ5758
STOP, don't go to 18.75KV										
15→0	13	12	1							Σ117

Table 17a: Manufacturer U: 5 Capacitor Module. (Each 1000pf, 10KV)
Resin Impregnated Mica



$C_{12} = 1040 \pm 20\text{pf}$

$C_{23} = 1010 \pm 20\text{pf}$

$C_{34} = 970 \pm 20\text{pf}$

$C_{45} = 1040 \pm 20\text{pf}$

$C_{56} = 1035 \pm 20\text{pf}$

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Table 17b. Manufacturer U: 5 Capacitor Module
Each 1000pf, 10KV

C_{12}

		2.6→300pc								
KV	ΣN	2.6→25	→50	→75	→100	→125	→150	→175pc		Σpc
0	0									
0→2.5	1	5.6pc								Σ5
2.5	0									
2.5→5	16	13	2						+66.4	Σ236
5	0									
5→7.5	43	41	2							Σ394
7.5	1	6.5pc								Σ6.5
7.5→10	69	57	6	1	1	1			+156,165 +243pc	Σ1490
10	2	1							+64pc	Σ84.8
10→12.5	90	72	8	2	5	3	(116pc highest)			Σ1794
12.5	5	3	1						+56.2pc	Σ137
12.5→0	66	55	7	1	1				+142,307pc	Σ1361

C_{23}

KV	ΣN	2.6→25	→50	→75	→100	→125	→150	→175pc		Σpc
0	0									
0→2.5	2	1		Starts at 2.4KV					+71pc	Σ74.5
2.5	0									
2.5→5	37	27	3	1	1	2			+175,180 +240pc	Σ1340
5	2		1		1					Σ116.9
5→7.5	72	59	4	1	2	3	1		+150,169pc	Σ1682
7.5	0									
7.5→10	96	74	8	3	4	3	1		+190,282 +290 +?	Σ2636
10	2	2								Σ13.4
		26→250pc			26→3000pc					
10→12.5	23	17							+421,472 +577pc	Σ4198
					2.6→300pc					
12.5	4	3							+60pc	Σ97
		26→250pc			26→3000pc					
2.5→0	26	23							+259,268 +322pc	Σ2609

C-2

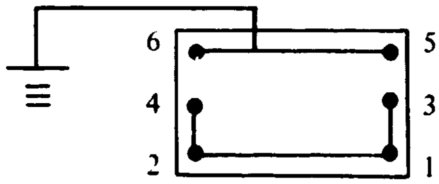
Table 17c. Manufacturer U: 5 Capacitor Module
Each 1000pf. 10KV

C34			2.6→300pc				
KV	ΣN	2.6→25	→50	→75	→100pc		Σpc
0→2.5	0						
2.5	0						
			Starts at 2.8KV				
2.5→5	18	12	4			+89,267pc +?	Σ584
5	0						
5→7.5	62	48	9	1	2	+120.7,255.3pc +?	Σ1394
7.5	4	3				+107.5pc	Σ126
			26→3000pc				
7.5→10	12	43	2 at 53,59,65,77,80,104,107,170,184,319pc				Σ1428
			2.6→300pc				
10	5	2	2			+108pc	Σ177
		26→208pc		26→3000pc			
10→12.5	23 .	20				2 at 350pc,514pc	Σ3240
				2.6 →300pc			
12.5	25	19	4			+94.3,216pc	Σ543
		26→182pc		26→3000pc			
12.5→0		24				+340pc	Σ2475

Table 17d. Manufacturer U: 5 Capacitor Module
Each 1000pf, 10KV

C_{45}

KV	ΣN	2.6→25	→50	→75	→100pc		Σpc



0→2.5	0		<u>2.6→300pc</u>				
2.5	0						
2.5→5	0						
5	0						
			Starts at 6KV				
5→7.5	3	2				+115.9pc	Σ158
7.5	1	1					Σ4
7.5→10	16	14	1			+184.8pc	Σ332
10	1	1					Σ4
10→12.5	23	21	1			+242.4pc	Σ456
12.5	1	1					Σ7
			<u>26→3000pc</u>				
12.5→0		6<	178pc			+592pc	Σ1290

Table 17e. Manufacturer U: 5 Capacitor Module
Each 1000pf, 10KV

C_{56}				2.6→300pc				
KV	ΣN	2.6→25	→50	→75	→100	→125pc		Σpc
0→2.5	0							
2.5	0							
2.5→5				Starts at 3.5KV				
2.5→5	26	25	1					Σ254
5	0							
5→7.5	97	84	7	2	1	1	+189,273.9pc	Σ1694
7.5	1	1						Σ4
		→200pc		26→3000pc				
7.5→10	11	6					+364,376,396,481 +1366pc	Σ3594
				2.6→300pc				
10	1	1						Σ9
		→200pc		26→3000pc				
10→12.5	24	15					+235,280,328,382 +391,643,1012,1072 +1117pc	Σ6868
				2.6→300pc				
12.5	6	5					+77pc	Σ108
		→200pc		26→3000pc				
12.5→0	30	26					+202,232,262,370, +685pc	Σ3795

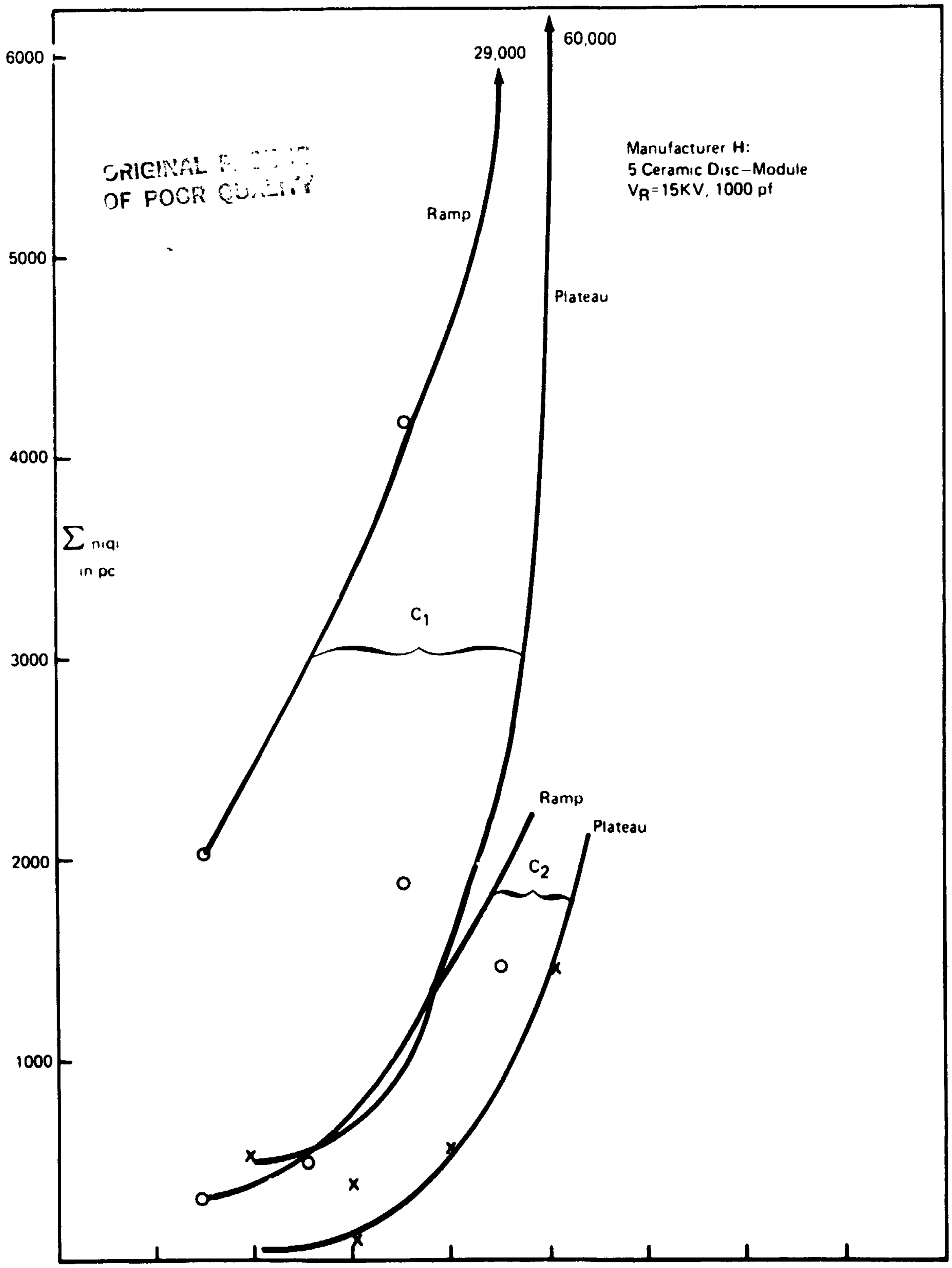


Figure 13. Partial Discharges as Function of Voltage.

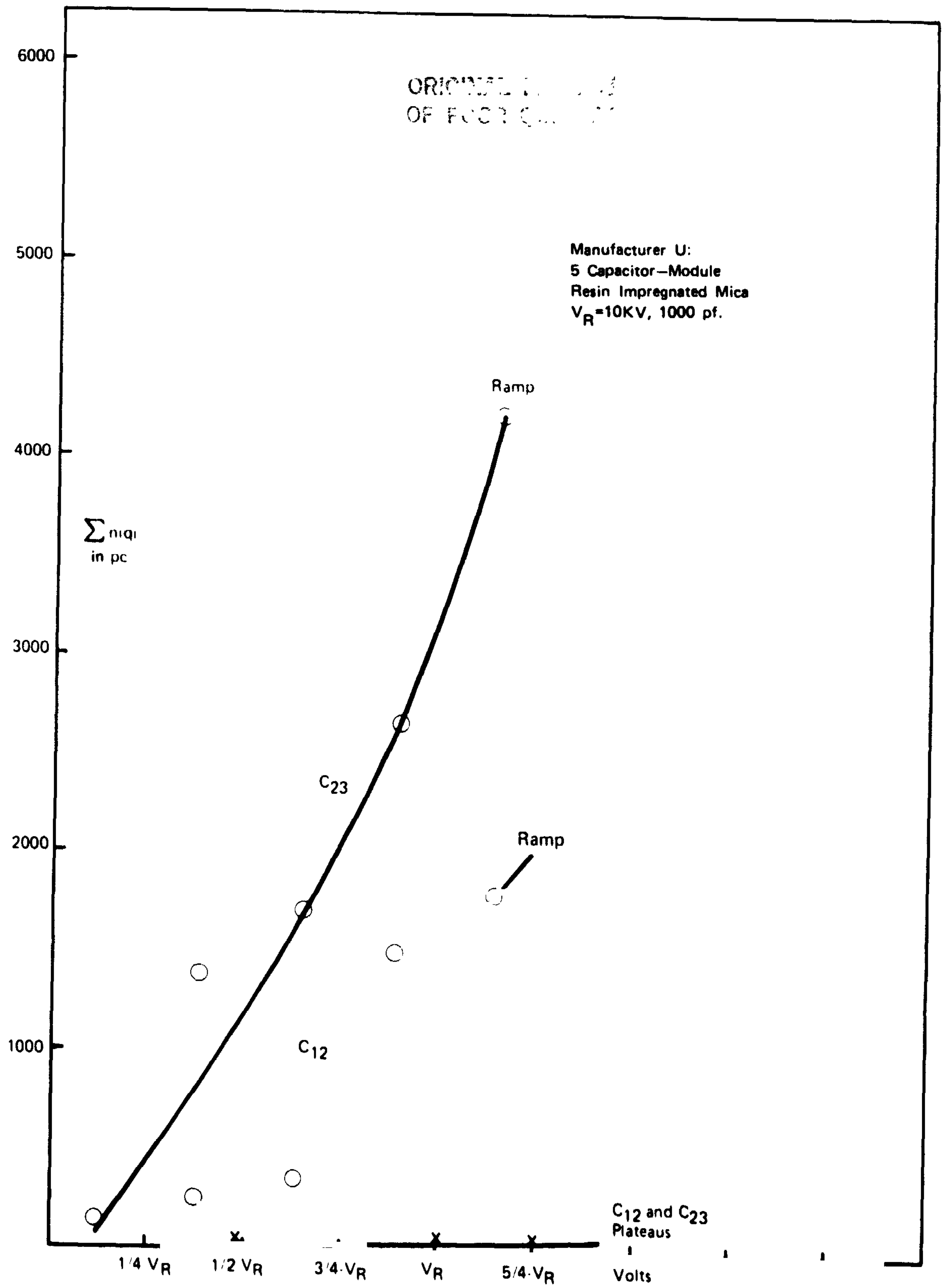


Figure 14. Partial Discharges as Function of Voltage.

ever, on the 3.75- 5 KV ramp the number and charge content of all the capacitors became so high that it appeared that there was a serious generic problem with all these capacitors irregardless of small cracks. Voids in the dielectric and excessive field strengths at the ends or edges of the interleaving capacitor plates seemed to be the problem. This is further born out by the fact that the worst partial discharge was experienced with two capacitors from Task 1-B-2-1 (my S/N #7 and #8) which were made with #325 mesh screen electrodes, between layers. This gave sharper edge definition than the usual #280 mesh and made edge fields stronger and partial discharges worse.

Trend studies in vacuum of the uncoated ones #2 and #4 showed that the improvement with time in vacuum was *not* real, but only apparent. Due to the usual polarization, space charge injection and ferroelectric nature of these $BaTiO_3$ ceramics, repeated tests in vacuum carried out with D.C. voltage applied in the same polarity give successively fewer P.D. pulses. However, as soon as the polarity was reversed on these capacitors in vacuum there was a reoccurrence of a tremendous number and charge content of pulses.

Doubling of layer thickness of the ceramic resulted in fewer counts and smaller charge content, but the voltage at which counts first appeared was still around 2.5 KV, the same as the original thin layer ones without cracks. Apparently the most significant origin of pulses is at and near the electrode edges where layer thickness does not greatly influence the field strength; mostly edge sharpness and interactions seem to create the pulses.

Multilayer ceramic capacitors are given a misleading rating by the manufacturers in that they all consistently break down at about 1.3 times V_R. Manufacturers' catalogues suggest that DWV (Dielectric Withstand Voltage) be tested at 1.2 V_R for these multilayers rather than at 2.5 V_R suggested for the single ceramic disc capacitors. The reliability margin is thus compromised by overrating by the manufacturers. The P.D. histograms on the ramps, however, show clearly that the P.D. pulses are excessive between $\frac{1}{2}V_R$ - V_R and are reasonable only from 0 - $\frac{1}{2}V_R$, where they are comparable to some single disc behavior from V_R - $3/2V_R$.

Life testing in vacuum of several manufacturers' multilayer stacked ceramic capacitors is now proceeding. These samples were P.D. tested before the Life test start and will be repeated after the 6 months' Life Test in vacuum at rated and slightly above-rated voltages. This should give some degree of confidence as to whether it is safe to use these capacitors near their rated voltage.

Tables 18a through 18v give the original data obtained in this investigation.

d) Some post-burn-in P.D. results on 2 batches of single disc ceramic capacitors

Table 19a-e reproduces some data excerpts of post-burn-in P.D. measurements on some single disc capacitors, $BaTiO_3$, 1000pf, X5R, 10 KV. These have remarkably little partial discharge, even on polarity reversal. The units that "failed" *visual* inspection initially (#29) or visual inspection after burn-in (#'s 4, 7, 20, 14) were also measured, interspersed with the "passed" units. The *visual* defects were cracks in the epoxy coating. These cracked coating units clearly had significantly more partial discharge activity, especially on the ramps. On this basis two units that passed all the customary post-burn-in tests such as Insulation Resistance measurement at 500 volts, short-term DWV, low voltage capacitance and dissipation factor measurements and visual inspection, should also be rejected, namely #'s 25 and 26.

Another set of capacitors were 1000pf, X5R, 20 KV $BaTiO_3$ discs. Table 20a-f shows some of their post-burn-in P.D. data. The term "pass" or "fail" is the screening contractor's verdict based on the tests named in the paragraph above or on initial pre-burn-in P.D. test. Again, S/N #1 which was failed on the basis of visible crack in the epoxy coating had a much more active P.D. histogram than #'s 2, 30, 5, 11, 16 and so on, that passed. Therefore, on the basis of the P.D.'s after burn-in #'s 14, 17, 8 and 15 also should be rejected although

Table 18a. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K, 10,000pf, 5KV

My numbers:	Man. K numbers		
	1)	280 hand-soldered leads (Pd, Pt, Ag)	
#1		#1 SLAM PASS–COATED	
#2		#2 SLAM FAILED	
#3		#3 SLAM FAILED–COATED	
#4		#4 SLAM PASSED	
	2)	TERMINATED PLATINUM PARTS	
#31		#11	SLAM PASSED
#32		#12	SLAM PASSED
		#13	SLAM PASSED
		#14	SLAM PASSED
	3)	280 MESH, TUNNEL KILN	
#5		#1 SLAM PASSED–COATED	1–A–1–1
#6		#2 SLAM PASSED	1–A–1–1
		325 MESH, TUNNEL KILN	
#8		#1 SLAM PASSES–COATED	1–B–2–1
#7		#2 SLAM PASSES	1–B–2–1
	4)	Specially Thick Layers	
#A		#A	
#B		#B	

Table 18b. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K, 10,000pf, 5KV
Naked #2K Worse one/Cracks

Naked #2K in Fluorinert

Voltage	ΣN	2→25	26→50	51→100	101→150	151→200	201→250	251→300	301→350	351→400	401→450	451→500	>500pc	Calib.
0→1.25	0													2→500pc
		2,3pc												
1.25	2	2												
1.25→2.5	53	36	6	9	2		Started in at 2.0KV							
2.5	3	3												
2.5→3.75	702	←	680		→	←	13	→	← 5 →	←	4	→	++	
3.75	4	4												
3.75→5	730	Maxwellian	→										++	
5	18	12	4	1			1							
5→0	41	31	5	2	1	2								

Immediate Repeat in Fluorinert on 6/8/82

Voltage	ΣN	2→25	26→50	51→100	101→150	151→200	201→250	251→300	301→350	351→400	401→450	451→500	>500pc
0→1.25	0												
1.25→2.5	1	1											
2.5	8	8											
2.5→3.75	9	6	3										
3.75	5	5											
3.75→5	126	←	112		→	3	5				1	4	
5	9	9											

Repeat in Fluorinert on 6/14/82

Voltage	ΣN	2→25	26→50	51→100	101→150	151→200	201→250	251→300	301→350	351→400	401→450	451→500	>500pc
0→1.25	0												
1.25	0												
1.25→2.5	1	1											
2.5	1	1											
2.5→3.75	132	←	120	→	6	Started at 2.8KV							
3.75	530	Maxwellian	→										++
5	7	7											
5→0	25	18	4	2	1								

Table 18c. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K. 10,000pf, 5KV
Soldered Lead Extensions with Heat Sinks on 6/21/82

Naked #2K Mounted in Vacuum system, atmosph P in air. 6/15/82

Voltage	ΣN	4→50	51→100	101→150	151→200	201→250	251→300	301→350	351→400	401→450	451→500	501→550	→600pc	Calib.
Long, new cables														4→1000pc
0	3	3												
0→1.25	1	1												
1.25	4	4												
1.25→2.5	24	22	2		Started at 1.9KV									
2.5	15	15												
2.5→3.75	35	34	1											
3.75	26	26												
3.75→5	193	135	30	11	3	1	3	2	0	1	0	1	1	775, 825pc
5	3	3												

Naked #2K Mounted in vac syst, atm P in air. 6/21/82

Voltage	ΣN	4→50	51→100	101→150	151→200	201→250	251→300	301→350	351→400	401→450	451→500	501→550	→600pc	Calib.
0→1.25	0	0												
1.25	0	0												
1.25→2.5	0	0												
2.5	0	0												
2.5→3.75	56	44	9	1		1	1	Started at 3KV						
3.75	0	0												
3.75→5	485	295	79	39	24	14	8	3	7	4	3	1	1	710,720 730,780pc
5→0	20	13	2	2		1	1	1						

After 18 hours in 10^{-5} torr vac., Naked #2KD. 6/22/82

Voltage	ΣN	4→50	51→100	101→150	151→200	201→250	251→300	301→350	351→400	401→450	451→500	501→550	→600pc	Calib.
0→1.25	5	3	2											
1.25	0	0												
1.25→2.5	2	2												
2.5	0	0												
2.5→3.75	31	29	2					Started at 3.1KV						
3.75	0													
3.75→5	199	141	32	11	9	3	1	0	1	2			1	875pc
5	1	1												
5→0	18	16					1	1						

Table 18d. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K, 10,000pf, 5KV

Naked #2K After 3 days in vacuum

Voltage	ΣN	4→50	51→100	101→150	151→200	201→250	251→300	301→350	351→400	401→450	451→500	501→550	→600pc	Calib.
0→1.25KV	0													4→1000pc
1.25	0													
1.25→2.5	0													
2.5	0													
2.5→3.75	19	18	1		Starts at 3.1KV									
3.75	0													
3.75→5	205	144	31	15	5	2	0	2			1	1		675,825 960,940pc
5	2	1		1										
5→0	10	8	1			1								

Naked #2K After 4 day in vacuum 6/25/82

Voltage	ΣN	4→50	51→100	101→150	151→200	201→250	251→300	301→350	351→400	401→450	451→500	501→550	→600pc	Calib.
0→1.25	0													
1.25	0													
1.25→2.5	0	1												
2.5	1	1												
2.5→3.75	19	18	1					Starts at 3.1KV						
3.75	0													
3.75→5	229	157	51	10	4	1	0	2	1				1	675pc
5	0													
5→0	11	9	1											

Table 18e. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K. 10.000pf. 5KV. Naked #2K. Opposite Polarity.

Voltage	ΣN	4→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700	→750pc
0→1.25	219	Most <160pc +186, 246, 380, 431, 787, 789pc											4→1000pc			
		Started at 600 volts														
1.25	1	32pc														
1.25→2.5	1255	799	216	85	52	20	18	8	7	7	6	5	3	4	5	
2.5	2	2														
2.5→3.75	989		765	97		30		15		4		6		8→2040pc		6
3.75	6	4												1		0
3.75→5	313	——— 240 ———→											40→10,000pc			
5	7	Most <220pc +2650, 3880, 9380, 9810+														
5→0	73	Most <50+ →100pc →150 →200 →250 →270, 360, 522pc														
					6		2	0		2						

Voltage	ΣN	→800	→850	→900	→950	→1000	Calibr.	→1100	→1200	→1300	→1400	→1500	→1600	→1700	→1800	→1900	→2000
0→1.25																	
1.25																	
1.25→2.5			3	1	1												
2.5																	
2.5→3.75					5	7		4	4	7	4	3	2	1	4	5	6
3.75										1							
3.75→5				29						9				4			
5																	
5→0																	

Voltage	ΣN	→2500	→3000	→3500	→4000	→4500	→5000	→5500	→6000	→6500	→7000	→7500	→8000	→8500	→9000	→9500	→10000
0→1.25																	
1.25																	
1.25→2.5																	
2.5																	
2.5→3.75																	
3.75																	
3.75→5		0	0	2	0	5	0	1	2	2	1	2	1	2	1	4	2
5			1		1											1	1

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Table 18f. 1982 Data. Multilayer Ceramic Capacitors
by Manufacturer K. 10,000pf. 5KV
Red Coated #1 Better One

Voltage	ΣN	2→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	Calibration	→700	→750	→800	→850	→900	→950	→1000pc
Red Coated #1K in Fluorinert																					
0→1.25KV	0													2→500pc							
1.25	0	0																			
1.2→2.5	38	27	7	4		Starts at 2.3KV															
2.5	4	4																			
2.5→3.75	1003	479	190	167	73	45	19	11	4	3											
3.75	18	11	1	4	1	1															
3.75→5	892	529	79	73	51	38	31	24	23	16	13	14	+++								
5	29	23	0	3	1	1						1									
5→0																					
Immediate Repeat in Fluorinert on 6/8/82																					
0→1.25	0																				
1.25	3	3																			
1.25→2.5	1	1																			
2.5	11	11																			
2.5→3.75	0	0																			
3.75	9	9																			
3.75→5	34	27	5	1	1																
5	14	12	0	1	1																
5→0	12	12																			
Inadvertant Polarity Reversal on 6/15/82														4→1000pc							
0→1.25	8	6	2																		
1.25	15	15																			
1.25→2.5	802	←———				789 ———			→To376		———		10 ——→				1				
2.5	9	5	2	2																	
2.5→3.75	1592	←———				Maxwellian to 1000pc ———															——→
3.75	33	←27→		4	1										1						
3.75→5	796					Maxwellian to 2000pc								8→2000pc ———							——→
5	32	←25→		2		2		1		1				1							
5→0	91	←80→		7	2	1	1														

Table 18g. 1982 Data. Multilayer Ceramic Capacitors
by Manufacturer K, 10,000pf, 5KV

6/21/82 Red Painted #1K Mounted in vacuum system, but at 760 torr

Voltage	ΣN	4→50	51→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600 Calibr. 4→1000pc	→650	→700	→750	→800	→850	→900	→950	→1000pc	
0→1.25	0																					
1.25	0																					
1.25→2.5	0																					
2.5	0																					
2.5→3.75	88	79	6	2	1		Starts in at 2.7KV															
3.75	1	1																				
3.75→5	482	288	68	32	26	11	10	5	5	8	8	4	2	0	4	2	2	2	1	4	5	+++
5	5	3																	1			
5→0	33	31	2																			

6/22/82 Red Painted #1K After being in vacuum for 18 hours, grounded

Voltage	ΣN	4→50	51→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700
0→1.25	0														
1.25	0														
1.25→2.5	0														
2.5	0														
2.5→3.75	9	9		Starts at 3.4KV											
3.75	0														
3.75→5	272	207	31	10	11	2	2	0	1	0	2	2	2	0	1
5	1	1													
5→0	30	29	1												

6/24/82 Red Painted #1K After in vacuum for 3 days

Voltage	ΣN	4→50	51→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700	→750	→800	→850	→900	→950	→1000pc
0→2.5,2.5	0																				
2.5→3.75	21	18	3	Starts at 3.5KV																	
3.75	0																				
3.75→5	270	194	46	10	2	5	1	1	1	0	1	0	1	0	1	0	1	0	0	1	1
5	0																				
5→0	23	21	1	1																	

Table 18h. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K, 10,000pf, 5KV

#1K Red Painted after 4 days at 10^{-5} torr vac.

Voltage	ΣN	→50	→100	→150	→200	→250	→300	→350	→400pc	Calibration
0→1.25	0									4→1000pc
1.25	0									
1.25→2.5	1	1								
2.5	0									
2.5→3.75	15	13		1			1	Starts at 3.4KV		
3.75	0									
3.75→5KV	177	125	32	10	3	1	1	2		
5	3	2			1					
5→0	25	22	3							

Table 18i. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K, 10,000pf, 5KV

Red Coated #3K in Fluorinert

Voltage	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600 Calibrate 2→500pc	→650	→700	→750	→800	→850	→900	→950	→1000pc
0→1.25	0																					
1.25	2	2																				
1.25→2.5	85	60	21	4	Starts at 1.8KV																	
2.5	1	1																				
2.5→3.75	1008	560	181	114	63	25	7	3	5	2	0	1										
3.75	13	8	1	1	1	2																
3.75→5	925	555	108	96	48	33	19	12	18	10	7	6+	+++									
5→0	52	← 52 →																				
Immediate Repeat in Fluorinert on 6/8/82																						
0→1.25	0																					
1.25	0																					
1.25→2.5	0																					
2.5	0																					
2.5→3.75	14	9	4	1																		
3.75	0																					
3.75→5	75	51	11	7	2	1	3															
5 (100sec)	15	7	4	3	1																	
5→0	77	67		8	1		1															
Repeat on 6/15/82														4→1000pc								
0→1.25	0																					
1.25	3	3																				
1.25→2.5	38	37		1			Starts in at 1.9KV															
2.5	8	7		1																		
2.5→3.75	114	99		12	3																	
3.75	3	3																				
3.75→5	434	270		74	35	10	5	5	6	4	3	2	4		1		1	1	2	2	1	++
5 (700sec)	88	77		5	2	1	2		1													
5→0	77	70		5	1	1																

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Table 18j. 1982 Multilayer Ceramic Capacitors
by Manufacturer K, 10,000pf, 5KV

Red Painted #3K, Mounted in vacuum system, but in air

Voltage	ΣN	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600 Calibrate 4→1000pc	→650	→700	→750	→800	→850	→900	→950	→1000
0→1.25	0																				
1.25	0																				
1.25→2.5	31	30	1	Starts at 1.9KV																	
2.5	0																				
2.5→3.75	111	105	5	1																	
3.75	1	1																			
3.75→5	448	293	69	25	16	7	3	5	3	2	1	2	3	1	2	2		2	1		1 +?
5	7	2		1	1	3															
5→0	56	49	6													1					
6/22/82	Red Painted #3K After being in vacuum for 18 hours, grounded.																				
0→1.25	0																				
1.25	0																				
1.25→2.5	18	17	1	Starts at 2.2KV																	
2.5	0																				
2.5→3.75	61	61																			
3.75	0																				
3.75→5	165	138	14	8	1		2									1					
5	0																				
5→0	45	40	2	1	2																
6/24/82	Red Painted #3K After being in vacuum for 3 days																				
0→1.25	0																				
1.25	0																				
1.25→2.5	11	9	2																		
2.5	6	4	1				1														
2.5→3.75	59	55	4																		
3.75	1	1																			
3.75→5	175	Erased.																			
5	0																				
5→0		34 counts Most <50 + →3 to 105pc																			

Table 18k. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K, 10,000pf, 5KV
6/25/82 #3K Red Painted After 4 Days at 10^{-5} torr vac.

Voltage	ΣN	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700	→750pc
														Calibr. 4→1000pc		
0→1.25																
1.25																
1.25→2.5																
2.5																
2.5→3.75	58	55	3	Starts out at 2.8KV												
3.75	0															
3.75→5	175	140	25	9	1		1	1								
5	1	1														
5→0	62	56	4		2											

6/25/82 Reverse Polarity

Voltage	ΣN	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700	→750
														Calib. 20→5000pc		
0→1.25	456	330	85	23	4		2	1				1				
1.25	0															
1.25→2.5	1373	867	258	110	59	21	10	4	6	2	7	1	1	1	1	5
2.5	6	5														
5→3.75	840	← 627 →					← 71 →					← 37 →				
3.75	3	1	1										1	4→1000pc 40→10,000		
3.75→5KV	386	← 267 →											← →			
	Combined (4→1000pc) (+40→10,000pc)													Combined (4→1000) (40→10,000pc)		
5	8	4			1		+8,570pc									
5→0	97	82	9	4		1								1	4→1000pc	

FOLDOUT FRAME

→750 pc

→750	→800	→850	→900	→950	→1000	→1250	→1500	→1750	→2000	→2250	→2500	→2750	→3000	→3250	→3500	→3750	→4000	→4
				1														
5	1	1	2		1	++												
——→	←———		17		———→	←22→	←14→	←8→	←9→	9	8	3	0	3	4	2	0	
———	48				———→	←—18	——→	←—7	——→	7			7		5		5	

00)
.0,000pc)

c

2 FO

→3750	→4000	→4250	→4500	→4750	→5000	→5500	→6000	→6500	→7000	→7500	→8000	→8500	→9000	→9500	→10,000
2	0		1	1	0										
	5		7		6	2	4	3	0	4	1	3	3	2	0

Table 181. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K, 10,000pf, 5KV
Naked #4K – Better one to start, Later cracks

Naked #4K in Fluorinert -40C

Voltage	ΣN	2→25	26→50	51→100	101→150	151→200	201→250	→300	→350	→400	→450	→500	>500	Calib.
0→1.25KV	0													2→500pc
1.25	6	6												
1.25→2.5	20	14	4	1 (77pc)		Starts at 2.3KV								
2.5	5	5												
2.5→3.75	706		696			1	4	3	1		1			
3.75	7	6		1										
3.75→5	630	——→											++	
5	25	19	4	1		1								
5→0	35	28	4	1			2							

Immediate Repeat in Fluorinert on 6/8/82

Voltage	ΣN	2→25	26→50	51→100	101→150	151→200	201→250	→300	→350	→400	→450	→500	>500	Calib.
0→1.25	0													
1.25	0													
1.25→2.5	7	7												
2.5	2	2												
2.5→3.75	2	2												
3.75	6	6												
3.75→5	28	17	4	3	2		1			1				
5	16	12	1			1		2						

Repeat in Fluorinert on 6/14/82

Voltage	ΣN	2→25	26→50	51→100	101→150	151→200	201→250	→300	→350	→400	→450	→500	>500	Calib.
0	1	1												
0→1.25	1	1												
1.25	3	3												
1.25→2.5	0													
2.5	3	3												
2.5→3.75	79	75	2	1	1	Starts at 3.3KV								
3.75	2	2												
3.75→5	417	——→											++	
5	12	1			1									
5→0	23	20	2											

Table 18m. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K, 10,000pf, 5KV
Soldered Lead Extensions with Heat Sinks on 6/21/82

Naked #4K Mounted in vacuum system, atm. P in air.

6/21/82		4→50	→100	→150	→200	Calibr:
0→1.25	0					4→1000pc
1.25	0					
1.25→2.5	0					
2.5	1	1				
2.5→3.75	123	66	48	6		
3.75	1	1				
3.75→5	BREAKDOWN on ramping. (Thought to be feedthru, but is #4K. See below.)					

6/25/82 #4K had gone along in vacuum for the ride connected into vac. system for 1st time this day. At 10^{-5} torr

0→1.25	0		
1.25	0		
1.25→2.5	2	2	
2.5	BREAKDOWN quiescently at 2.5KV		

Again, on different feedthru about 1 hr later at 10^{-5} torr

6/25/82						
0→1.25	0					
1.25	0					
1.25→2.5	89	64	16	7		2
2.5	1	1				
2.5→3.75	BREAKDOWN at 3.4KV					

Table 18n. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K, 10,000pf, 5KV

6/25/82 Same day, in Fluorinert Again, #4 K.

Voltage	ΣN	0→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→517	→600	→650	→700	→750
														<u>Calibr</u> <u>4→1000pc</u>		
0→1.25	83	67	10	3								1				
1.25	0															
1.25→2.5	1088	710	222	87	30	11	5	2	1	3	3	1	2	+725,775 +925		
2.5	12←	6	1		1	2			1		1					
2.5→3.75	1222	Maxwellian to 1000+														
3.75	15←	5	5	5												
3.75→5	525						365							<u>40→10,000pc</u>		
5	15	7	3			1			1			2				
5→0	499															

Voltage	ΣN	→800	→850	→900	→950	→1000	→1500	→2000	→2500	→3000	→3500	→4000	→4500	→5000	→5500	→6000
0→1.25																
1.25																
1.25→2.5																
2.5																
2.5→3.75																
3.75																
3.75→5		87					15	5	7	5	3	6	2	0	4	5
5					1											

Voltage	ΣN	→6500	→7000	→7500	→8000	→8500	→9000	→9500	→10,000pc
0→1.25									
1.25									
1.25→2.5									
2.5									
2.5→3.75									
3.75									
3.75→5		7	5	4	1	2	2	3	1
5									

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Table 18o. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K, 10,000pf, 5KV
Man. K#12. Naked, No Leads. (Use Cu Tape) 10,000pf, 5KV, Stacked Monolithic (My S/N 32)

Voltage	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700
														Calibr: 4→1000pc		
.15→1.25	0															
1.25	0															
1.25→2.5	55	29		10	4	8	2		2	Starts at 1.7KV						
2.5	0															
2.5→3.75	460	387		40	12	7	10	3	1		1					
3.75	9	8		1								~3pc/sec				
														40→10,000pc		
3.75→5	309							242								
5KV(1)	10	4			1	1	2			+1450,1960						
														4→1000pc		
5KV(2)	9	7	1	1												
5→0KV	66	52		8	2	3	1									

Voltage	ΣN	→750	→800	→850	→900	→950	→1000	→1500	→2000	→2500	→3000	→3500	→4000	→4500	→5000	→5500
.15→1.25																
1.25																
1.25→2.5																
2.5																
2.5→3.75																
3.75																
3.75→5		32						11	5	2	3	1	2	1	1	1
5KV(1)																
5KV(2)																

Voltage	ΣN	→6000	→6500	→7000	→7500	→8000	→8500	→9000	→9500	→10,000
.15→1.25										
1.25										
1.25→2.5										
2.5										
2.5→3.75										
3.75										
3.75→5		2		2					2	
5KV(1)										
5KV(2)										

Table 18p. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K, 10,000pf, 5KV
K#11. Naked, No Leads. (Use Cu Tape) 10,000pf, 5KV
(My S/N 31)

Voltage	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→500	→500	→550	→600	→650	→7(
.15→1.25	5	3		1		1									Calibr. 4→100pc	
1.25	1	1									Starts at 1.4KV					
1.25→2.5	428	331		48	26	11	4	1	4	3	0	0	1	0	3	0
2.5	9	6	1		1											
2.5→3.75	1572	1183		151	48	23	18	21	15	10	13	12	7	13	10	5
3.75	3	2	1													
3.75→5	427		←					282				→	←		40→10,000pc	→
5	4	3	1													
5→0KV	131	98		16	7	5	1				1				4→1000pc	2

Voltage	ΣN	→750	→800	→850	→900	→950	→1000	→1500	→2000	→2500	→3000	→3500	→4000	→4500	→5000	→5500
.15→1.25																
1.25																
1.25→2.5		2	0	0	1	0	0									
2.5					1											
2.5→3.75		6	6	1	5	5	3									
3.75																
3.75→5	←	47					→	19	7	8	13	5	8	8	3	2
5																
5→0KV				1												

Voltage	ΣN	→6000	→6500	→7000	→7500	→8000	→8500	→9000	→9500	→10,000
.15→1.25										
1.25										
1.25→2.5										
2.5										
2.5→3.75										
3.75										
3.75→5		1	5	5	1	1	3	3	2	1
5										
5→0KV										

Table 18q. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K, 10,000pf, 5KV
Task 1-A-1-1 Group IA #2, (My S/N #6), Naked, INK Lot 1648.

Voltage	ΣN	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650 Calibr. 4→1000pc	→700	→750
0→1.25	0															
1.25	0															
1.25→2.5	458	354	78	18	2	3	1	Starts at 1.8KV			1					
2.5	8	6	1												1	
2.5→3.75	1530	< 1104 >		< 291 >		< 72 >		< 33 >		< 8 >		< 7 >		< 5 >		
3.75	9	5	2	1				1								
3.75→5	997	625		136		67		36		29		18		12		
5	10	7	2			1										
5→0	95	92		3												

Voltage	ΣN	→800	→850	→900	→950	→1000	→1100	→1200	→1300	→1400	→1500	→1600	→1700	→1800	→1900
0→1.25															
1.25															
1.25→2.5															
2.5															
2.5→3.75		< 5 >	< 2 >			< 1 >	< 1 >			< 2 >					
3.75															
3.75→5		6	5		7	9		2	4	9	3	2	7	7	2++
5															
5→0															

Table 18r. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K. 10,000pf, 5KV
Task 1-A-1-1 Group IA #1. (My S/N # 5), Red Coated, INK Lot 1648.

Voltage	ΣN	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700	→750
0→1.25	0													Calibr.		
1.25	0													4→1000pc		
1.25→2.5	293	267	22	3	2			2	3	Starts at 1.8KV						
2.5	6	6														+775pc
2.5→3.75	1633	< 1273	>	< 215	>	< 78	>	< 31	>	< 11	>	< 8	>	< 5 (8→2000pc)	>	
3.75	4	1	1		1		1									
3.75→5KV	681	←				476						→	←	56 (40→10,000pc)		
5KV	1				1											
5→0	13	<	9	>		1									1	

Voltage	ΣN	→800	→850	→900	→950	→1000	→1100	→1200	→1300	→1400	→1500	→1600	→1700	→1800	→1900	→2000
0→1.25																
1.25																
1.25→2.5																
2.5																
2.5→3.75		< 7 >	< 1	>	< 1 >	< 2 >	< 1 >	< >	< 1 >	< 0 >	< 2 >	< 3 >	< 1 >	< 1 >	< 0 >	< 0 >
3.75																
3.75→5KV		←				→ ←		41		→						
5KV																20
5→0																

Voltage	ΣN	→2500	→3000	→3500	→4000	→4500	→5000	→5500	→6000	→6500	→7000	→8000	→8500	→9000	→9500	→10,000
0→1.25																
1.25																
1.25→2.5																
2.5																
2.5→3.75																
3.75																
3.75→5KV		16	15	13	10	8	9	7		4	1	1	1	1	1	1
5KV																
5→0																

More discharges and higher energies than the naked one correspondingly. (My S/N #6)

ORIGINAL PAGE IS
OF POOR QUALITY

Table 18s. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K, 10,000pf, 5KV
Task 1-B-2-1 Group IB #1, (My S/N #8), Red Coated, INK Lot 1649.

Voltage	ΣN	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700	→750
														Calibr.		
0→1.25	5	1			1			1	Starts below 1KV			1		4→1000pc		
1.25	0															
1.25→2.5	1530	1069	251	83	38	14	11	12	4	4	3	0	1	1	0	2
2.5	1	1														
														20→5000pc		
2.5→3.75	270					250					< 15 >					
3.75	2		1	1										40→10,000pc		
3.75→5	555	←				390					→	←				→
5	8					4			1			1			1	
5→0	92															

Voltage	ΣN	→750	→800	→850	→900	→950	→1000	→1200	→1300	→1400	→1500	→2000	→2500	→3000	→3500	→4000
0→1.25																
1.25																
1.25→2.5		2	0	1	0	0	1									
2.5																
							2		2	+3000pc						
2.5→3.75					2					+3125pc	2					
3.75																
3.75→5			70				→	←	25		→	17	17	17	7	14
5			1													
5→0			3							+1840, 4310pc						

Voltage	ΣN	→4500	→5000	→5500	→6000	→6500	→7000	→7500	→8000	→8500	→9000	→9500	→10,000
0→1.25													
1.25													
1.25→2.5													
2.5													
2.5→3.75													
3.75													
3.75→5		6	6	8	4	2	5	1	2	0	1	1	0
5													
5→0													

Table 18t. 1982 Data: Multilayer Ceramic Capacitors by Manufacturer K. 10.000pf. 5KV
Task 1-B-2-1 Group IB #2. (My S/N #7), Naked, INK Lot 1649.

Voltage	ΣN	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	→700	→750
														Calibr.		
0→1.25KV	10	6						1	Starts in at 1.2KV					4→1000pc		
1.25	0															
1.25→2.5	556	430	73	21	8	5	3	4	2	0	2	0	1	0	2	1
2.5	10	7	1			1								1	1	
2.5→3.75	1909	< 1484	>	< 212	>	< 78	>	< 34	>	< 24	>	< 18	>	< 15	>	
3.75	7	3	4													
3.75→5	826	←	550		→	←	183		→	←	50		→	←	29	
														16→4000pc		
5KV	15	5	3	1		1					1					1
5→0	76	←	58		→	←	5		→	<		3	>			2

Voltage	ΣN	→800	→850	→900	→950	→1000	→1100	→1200	→1300	→1400	→1500	→1600	→1700	→1800	→1900	→2000
0→1.25KV																
1.25																
1.25→2.5		0	0	0	1	0										
2.5																
2.5→3.75		< 14 >	< 7	>	< 3	>	< 11 >	< 2 >	< 2 >	< 5 >	< 0 >	< 3 >	< 2 >	< 1 >	< 0 >	< 0 >
3.75																
3.75→5		→	←	11		→	←	13 →	← 8	→	← 4 →	→		7		6
5KV				1						1	+2436pc					
5→0		<		2		>	<	2	>					1		0

Voltage	ΣN	→2200	→2400	→2600	→2800	→3000	→3200	→3400	→3600	→3800	→4000
0→1.25KV											
1.25											
1.25→2.5											
2.5											
2.5→3.75											
3.75											
3.75→5		3	5	9	5	6	1	2	3	2	3++
5KV											
5→0		1	0	0	1	0	0	0	0	0	0

TERRIBLE PERFORMANCE

Table 18u. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K,
Special Doubly Thick Layers, 3000pf, 5KV, Naked Leads

#A

Voltage	ΣN	4→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Calib.
0→1.25	0														
1.25	0														4→1000pc
1.25→2.5	10	8		1	1	Starts at 2.4KV									
2.5	1														
2.5→3.75	402	314		61	17	5	1	1	1			1			
3.75	4	4													
3.75→5	511	341		61	36	24	8	14	8	4	5	3	2	1	1+875pc
5	0														
5→0	6	3			1				1				1		

Table 18v. 1982 Data: Multilayer Ceramic Capacitors
by Manufacturer K,
Special Doubly Thick Layers, 3000pf, 5KV, Naked Leads

#B Voltage	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	→650	Calib.
																4→1000pc
.15→1.25	1	1														
1.25	0															
1.25→2.5	14	14				Starts at 2.4KV										
2.5	0															
2.5→3.75	497	376		83	20	2	4		1	1				1		675pc
3.75	8	4		2	2											
3.75→5	443	266		56	30	20	17	10	8	6	2	7	1	2	1	675,725pc
5	12	9				2	1									
5→0	0															

Table 19a.: Post Burn-in P.D. Measurement
Calib: 1.4→300PC cal at 0 KV
Manufacturer M: 1000pf X5R 10KV

V KV	ΣN	1.4→12	→25	→50	→75	→100	→125	→150	$\Sigma n_i q_i$ pc
#3									
0→5	0								
5	0								
5→10	1	4.3pc							
10	0								
10→0	0								
Reverse Polarity							Reverse Again		
0→5	0								
5	0								0 again
5→10	0								
10	0								
10→0	0								
#8									
0→5	0								
5	0								
5→10	28	24	4						Σ214.pc
St at 7KV									
10	1	1.4pc							Σ1.4pc
10→0	4	1	2					+33pc	Σ76.9
#27									
0→5	4	4							Σ27.9
St at 3KV									
5	0								
5→10	52	44	5	3					Σ383
10	4	4							Σ22.3
10→0	3	3							Σ15.6

Table 19b.: Post Burn-in Measurement
HV Cal Cap: 0 KV Cal: 1.4→300pc

V	ΣN	1.4→12	→25		
#13					
0→5	2	2			Σ7.6pc
St at 4KV					
5	0				
5→10	0				
10	0				
10→0	0				
Reverse Polarity					
0→5	0				
5	0				
5→10	2	2			Σ7pc
10	1	1			Σ3pc
10→0	0				
#24					
0→5	2	1.4,2.6			Σ5pc
5	0				
5→10	1	5			Σ5pc
10	0				
10→0	4	3	1		Σ21.5pc
#5					
0→5	0				
5	1	4.7			Σ4.7pc
5→10	0				
10	1	4.7			
10→0	0				
#21					
0→5	0				
5	0				
5→10	4	3		+ 58pc	Σ67.5
10	0				
10→0	0				

Table 19c: Post-Burn-in P.D. Measurement
Recalibrate 1.2→200pc
With Low Voltage Cal Cap

V	ΣN	1.5→9	9→17	17→33	34→50	50→67		
#17								
0→5	0							
5	0							
5→10	0							
10	9	9						Σ19.8
10→0	0							
F#20	Crack in Coating							
0→5	32	25	5	2				Σ212.
5	5	4					+16.4	Σ27.
5→10	181	141	21	13	3	1	+94,121pc	Σ1482.
10	14	6	3	5				Σ168.
10→0	59	55	4					Σ235.8
#12								
0→5	0							
5	0							
5→10	0							
10	14	7	0	7			+24.8	Σ209
10→0	1							Σ1.9pc
F#29								
0→5	1		1					
5	21	16	3	2				Σ115.
5→10	18		5	2	2			Σ216.
10	19	3pc						Σ399.
	20	2	7	11				Σ426.
10→0	6	4	1	1				Σ55.5

V	ΣN	1.5→9	9→17	17→33	34→50	51→67		
#26								
0→5	1	2.0pc						
5	0							
5→10	53	41	2	2	1	1	+135pc	Σ876.
10	0							
10→0	3	3						Σ10.
#15								
0→5	0							
5	0							
5→10	0							
10	0							
10→0	0							
#22								
0→5	0							
5	0							
5→10	0							
10	0							
10→0	0							
#11								
0→5	0							
5	0							
5→10	0							
10	0							
10→0	1	1						

Table 19d. Post Burn-in P.D. Measurement
1.2→200pc

V	ΣN	1.2→9	9→17	17→33	34→50	→66	→83		
#4									
St. at 3KV									
0→5	40	31	8	1					Σ236
5	1	3							
5→10	153		26	2	5	1		+75pc	Σ1196.
10	14	9	6	1				+38pc	Σ150.
10→0	42	36	4	1	1				Σ237.
#6					Reverse				
0→5	0		0→5		1	3.1pc			
5	0		5	29	29				Σ104.
5→10	0		5→10	11	7	0	2	+64	Σ164.
10	0		10	18	8	10			Σ161.
10→0	0		10→0	0					
					Reverse again				
0→10				23	19	1	2	+84.9	Σ245

Run reversed on #'s 1 and 2

V	ΣN	1.2→9	9→17	17→33	
#1					
0→5	1	1.9pc			
5					
5→10	1	2.3pc			
10	0				Σ7.3
10→0	0				
Reverse					
0→10	24	21	3		Σ129.6
10	11	4	7		Σ88.9
10→0	0				
#2					
0→5	1	2.3pc			
5	0				
5→10	3	3			Σ9.4
10	13	6	6	1	Σ120.5

V	ΣN	1.2→9	9→17	17→33	34→50	→66	→83pc		
Reverse									
0→10	42	39	2					+118	Σ245.6
10	27		11					+41.7	Σ227.2
#28 Reversed									
0→5	0								
5	0								
5→10	17	11	2	1	0	3			Σ239.5
10	15	6	9						Σ166.6
10→0	1	2.3pc							
Reverse again									
0→10	29	18	4	3	3	1			Σ397
10	7	7							Σ12.
10→0	0								
#19 Reversed									
0→5	9	7	1	1					Σ69.
5	10	10							
5→10	12	7	1	4					Σ134
10	6	6							Σ10.7
10→0	1	2.4pc							
Reverse again									
0→10	55	40	5	10	29.0				Σ440
10	2								Σ8.6
#18 Reversed									
0→5	Missed								
5	0								
5→10	50	34	3	3	4	3	2	+85.7	Σ762
10	12	11	1						
Reverse again									
0→10	36		3	4	2	3		+89pc	Σ547
10	6	6							Σ14.8
10→0	1	5	1pc						

Table 19e. Post Burn- in P.D. Measurement
1.2→200pc
Low Volt Cal Cap

#16 Reversed

KV	ΣN	1.2→8	→16	→33	→49	→66	→83	→100		
0→5	0									
5	0									
5→10	9	8							+24.3	Σ50.6
10	0									
10→0	1	2.5pc								

Reverse Again

0→10	11	10							+31.7	Σ58.9

#25 Same Polarity

0→5	0									
5	0									
5→10	1322 (Burst)	1015	227	73	4	1	0	0	+144	Σ7955
10	1	1.5pc								
10→0	0									

#10 Same Polarity

0→5	2	1.7, 4.7pc								Σ6.4
5	2	2.2, 2.4pc								Σ4.6
5→10	0									
10	0									
10→0	5	5								Σ11.8

#30 Same Polarity

0→5	0									
5	0									
5→10	0									
		3.3	9.5							
10	2	1	1							Σ12.8

#23 Reversed

0→5	0									
5	0									
5→10	9	8							+45.3pc	Σ63.
10	3	3								Σ6.5
10→0	1	1.3								

KV	ΣN	1.2→8	→16	→33	→49	→66	→83	→100pc		
Reverse Again										
0→100	5	5								Σ29.7
10	1	1.9pc								
#6 Same Polarity										
0→5	0									
5	0									
5→10	10	8							+50.5,118.8	Σ190
10	2	2.3, 2.9pc								
10→0	1	2.1pc								
F #7 Same Polarity										
0→5	477		109	44	20	2	2		+90.6pc	Σ4600
Start at 2.5KV										
5	0(!)									
5→10	894	557	170	139	22	6				Σ8379
10	17	10	1	5					+52	Σ231.6
10→0	496		93	46	2				+55.7	Σ3606

Table 20a. 1984 Data: Final Post-Burn-in P.D. on Manufacturer M. 1000pf, 20KV, X5R discs
Tag+, Calibr: 3.5→600pc

#14 Pass

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600pc	Σpc
0→10	72	33	12	8	9	5	4	0	$\frac{280pc}{1}$							Σ3801.
Starts at 4KV																
10	88	87	6													Σ1098
10→13	46	26	8	5	1	1	2	0	2	1						Σ2353
13	126	104	20	2												Σ1925
13→17	76	47	7	10	3	4	3	1	1	$\frac{291pc}{1}$						Σ3098
17	193	159	24	8	1	$\frac{113pc}{1}$										Σ3299
17→0	35	29	3	8	3	$\frac{123pc}{2}$										Σ1403

DOUBTFUL

#17 Pass

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600pc	Σpc
0→10	282	194	21	14	6	8	8	7	4	4	4	4	1	3	$\frac{598pc+}{3}$	Σ18020
Starts at 4KV																
10	31	29	2													Σ308
10→13	91	63	10	1	2	4	2	3	0	2	0	0	0	1	$\frac{570pc+}{2}$	Σ5501
13	56	56														Σ568
13→17	148	102	17	11	1	4	3	4	2	0	2	1			+539pc	Σ6571
17	106	92	14													Σ1418
17→0	254		27	5	7	8	6	7	4	7	4	4	2	0	4 +602pc	Σ16881

NO

#9 Pass

V	ΣN	→25	→50	Σpc
0→10	9	7	2	Σ66.5
Starts at 8KV				
10	0			
10→13	5	4	1	Σ93

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600pc	Σpc
13	4															
13→17	11	9	0	2												Σ26 Σ260
17	24	23	$\frac{29.3}{1}$													Σ222
17→0	1	0	$\frac{31.2}{1}$													
#25 Pass																
0→10	2	2														Σ25
Starts at 9KV																
10	4	4														Σ23
10→17	29	26	3													Σ389
17	45	43	2													Σ471
17→0	0															
#8 Pass																
0→10	170		27	22	13	9	9	7	6	1	1	5	0	1	+581pc	Σ16225
Starts at 4KV																
10	0															0
10→17	215		33	23	16	6	11	7	2	3	1	1	3	1	+601pc	Σ16206
17	29	28	$\frac{26pc}{1}$													Σ271
17→0	330	206	55	35	14	8	3	2	3	2	$\frac{+436pc}{2}$					Σ13795
NO																
#5 Pass																
0→10	4	4														Σ58
Start at 9KV																
10	3	3														Σ30.9
10→17	40	34	6													Σ584
17	76	72	4													Σ953
17→0	0															
Reverse Polarity																
0→10	0															
10	0															

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OF POO[illegible]

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
10→17	21	18	2	98pc/1												
17	25	25														Σ325
17→0	0															Σ220
#11 Pass																
0→10	4	2	1													
Starts at 8KV											+188pc					Σ237
10	1	1														
10→17	34		4	3	0	2										Σ13.7
				58.1/1							+555pc					Σ1535
17	6	5	0													
17→0	0															Σ115.8
#16 Pass																
0→10	0															
10	0															
10→17	8	8														
Starts at 15KV																Σ76
17	22	22														
17→0	0															Σ204
#27 Pass																
0→10	11	9	2													
Starts at 8KV																Σ134
10	0															
10→17	69	53	12	84pc/4												
17	55	50	5													Σ1319
17→0	6	5	1													Σ741
																Σ118
#22 Pass																
0→10	0															
10	0															
10→17	28	24	4													
Starts at 12KV																Σ407
17	17	15	2													
17→0	0															Σ250.9

Table 20b. 1984 Data: Final Post-Burn-in P.D. on Manufacturer M, 1000pf, 20KV, X5R discs

#21 Failed on Initial P.D.

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
0→10	0															
10	0															
10→17	2	2														
Starts at 14																
17	0															Σ20
17→0	0															

OK

Reverse Polarity

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
0→10	0															
10	0															
10→17	1	1														
17	2	2														
17→0	0															Σ14.9
																Σ31.5

#19 Failed on Initial P.D. Tag +

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
0→10	0															
10	1	1														
10→17	34	26	6		2	62pc										Σ11.3
Starts at 12KV																
17	25	22														Σ632
17→0	4															Σ387
																Σ72

OK

#7 Failed on Initial P.D. Tag +

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
0→10	0															
10	0															
10→17	2	2														
Starts at 15KV																
17	5	5														Σ45.3
17→0	0															
																Σ54.7

OK

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
#2 Pass																
0→10	86	59	22		4	$\frac{115pc}{1}$										Σ1867
Starts at 4KV																
10	0															
10→17	102	72	26		4											Σ2135
17	5	5														Σ39
17→0	63	61	2													Σ789
#15 Pass																
0→10	574		129		118	43	17	12	9	7	14	5	3	3	$+\frac{586pc}{1}$	Σ42240
Starts at 2KV																
10	0															
10→17	394	133	119		62	25	9	8	11	18	3	$\frac{435pc}{6}$				Σ2936
17	9															Σ89.7
17→0	1115	547	313		199	48	6	$\frac{231pc}{2}$								Σ40010
NO																
#2 Pass																
0→10	11	11														Σ124.9
Statts at 8KV																
10	0															
10→17	70	60	10													Σ1084
17	5	5														Σ38
17→0	65	58	7													Σ828
#30 Pass																
0→10	16	11	3		$\frac{55pc}{2}$											Σ367
Starts at 6KV																
10	1	1														Σ3.5
10→17	69	52	13		$\frac{92pc}{4}$											Σ1340
17	13	12			+68.9											Σ215.9
17→0	18	18														Σ161

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→600	Σpc
#24 Failed															
Starts at 1KV															
0→10	430	327	62	18	11	10	4	1	2	3	1			+512pc	Σ12286
10	34	33	1												Σ384
10→13	81	55	12	11	1	0	185pc/2								Σ2300
13	67	62	5												Σ760
13→17	111		14	6										+224pc	Σ2157
17	135	123	11												Σ1769
17→25	203	163	29	4	3	2	1							+295pc	Σ3996
25	297	230	55	10	2										Σ5013
Peaks at 25pc															
25→0	529	306	93	34	33	27	10	8	5	3	4	5	513pc/1		Σ24590
#28 Failed															
0→10	70	25	15	10	3	8	4	4	271pc/1						Σ4710
Starts at 4KV															
10	12	12													Σ112.8
10→13	23	6	3	4	1	3	3	3							Σ2169
13	39	39													Σ380
13→17	35	11	3	4	3	4	4	2	282pc/4						Σ3373
17	68	62	6												Σ874
17→25	107	60	18	6	3	5	3	5	3	3				+383pc	Σ6222
25	180	162	16	1	79pc/1										Σ2373
25→0	81		9	10	3	6	10	7	4	3	3	1		+490,502pc	Σ9891

Table 20c. 1984 Data: Final Post-Burn-in P.D. on Manufacturer M, 1000pf, 20KV, X5R discs
(MDC 1000 MX5R 20KV)

#10 Failed

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
0	0															
0→10 (15sec+5)	2		1			110pc/1										Σ149
10 (100sec)	14	14														Σ110
10→17	37	34	1	1	0	1										Σ586
17	118	113	5													Σ1252
17→25	85	61	13	4	0	2	2						+243pc			Σ2196
25	261	216	34	9	86.3pc/2											Σ4272
25→0	10	10														Σ99.8
Reverse Polarity																
0→10 Starts at 4KV	35	27	5	1	1	0	181pc/1									Σ795
10	5	5														Σ27
10→13	11	9	0	0	0	114pc/1										Σ226
13	25	24	1													Σ254
13→17	27	20	4	1	0	2										Σ692
17	64	62	1										+173pc			Σ817
17→25	89	66	14	3	4	0	0	245pc/2								Σ2182
25	158	150	8													Σ1840
25→0	7	2	2	0	100.7pc/3											Σ365

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Table 20d. 1984 Data: Final Post-Burn-in P.D. on Manufacturer M. 1000pf. 20KV. X5R discs (Tag on (–). (HV Terminal)

#3 **Failed: Much P.D. Initially**

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	$\Sigma n_i q_i$
0	0															
0→10	187			Erased by Mistake										To +600pc		Σ11892
10	41	41														Σ319
10→13	110	71	19	6	6	2			2	1			+534,538			Σ5040
Peaks at 28pc																
13	115	113	2													Σ1260
13→17	165	100	34	7	7	6	3	1	3	0	2	1	+587			Σ7317
Peaks at 25pc																
17	216	192	22	2												Σ2964
17→25	437	294	64	30	17	13	5	3	2	0	3	3	0	2	+551pc	Σ16457
Peaks at 40,50pc																
25	480	333	89	35	16	6									+155pc	Σ11121
25→0	402(!)	261	49	28	8	12	9	8	6	6	3	0	5	5		Σ23237

Table 20e. 1984 Data: Final Post-Burn-in P.D. on Manufacturer M. 1000pf, 20KV. X5R discs

#3 Failed, Tag +

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
0→10	356		52	35	15	6	6	0	0	5	4	1	1	3	+602pc	Σ17160
Starts at 1.5 KV																
10	0															
etc																
etc																
10→17	258	167	50	18	10	4	3	2	1	0	0	1	2	0	+603pc	Σ10220
17	2	1		1												
17→0	219		30	31	6	7	3	6	1	0	1	4	0	3	+608pc	Σ13391

NO

Table 20f. 1984 Data: Final Post-Burn-in P.D. on Manufacturer M. 1000pf. 20KV. X5R discs
(MDC 1000M X5R. 20KV)

#1 Fail - Cracked Epoxy coat on Final Visual

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
0→10	1156	802	176	95	30	20	4	7	4	1	2	2	1		+553pc	Σ39598
Starts at 1KV																
10	3	3														
10→13	89	58	18	11	1	1	171pc / 1									Σ14.7
13	19	19														Σ2425
13→17	104	79	14		9											Σ135.5
17	56	55	1											+346,363pc		Σ2726
17→0	568(!)		101		109	45	17	10	7	2	2	1		+561pc		Σ528 Σ29727
Same Polarity																
Starts at 2.5KV																
0→10	434		57		24	8	3	2	4	0	1	1		+607pc		Σ10,981
10	18	15	0		2									+190pc		Σ471
10→17	276	229	21		13	7	1	0	2	0	400pc / 2					
17	58	58														Σ6817
17→0	829		94		91	35	13	5	12	8	1	2	0	3	+612pc	Σ581 Σ34149
Reverse Polarity																
0→10	816	465	119		127	53	22	15	4	6	2	0	2	571 pc / 1		Σ37103
10	0															
10→17	189		25		19	5	4	2	1							
17	42	42													+305pc	Σ5952
17→0	966	712	89		56	32	11	16	!4	6	13	5	6	4	2++	Σ366 Σ41071

V	ΣN	→25	→50	→75	→100	→150	→200	→250	→300	→350	→400	→450	→500	→550	→600	Σpc
#7 Failed																
0→10	4	4														Σ33
Starts at 9KV																
10	37	37														Σ383
10→13	15	14	32pc/1													Σ161
13	72	68	35pc/5													Σ840
13→17	24	21	2	55pc/1												Σ357
17	164	141	22	52pc/1												Σ2271
17→25	102	83	12	4	3											Σ1818
25	429	347	61	16	4	22pc/1										Σ7174
25→0	3	3														Σ41
#26 Failed																
0→10	15	14	1													Σ163
Starts at 7.5KV																
10	37	37														Σ364
10→13	12	10	2													Σ177
13	55	52	3													Σ587
13→17	25	20	4	1												Σ405
17	98	93	5													Σ1207
17→25	88	72	10	3	85pc/3											Σ1585
25(1)	260	212	42	72pc/6												Σ3902
Peak at 30.5pc																
25(2)	247	211	29	6	90pc/1											Σ3648
25→0	1		1													Σ47

they are within specifications on all the other tests. "Fail" in the above two paragraphs means "rejection". None of the capacitors tested or screened actually failed electrically in a catastrophic way, during the tests or screening procedures.

The capability of D.C. partial discharge measurements to detect damage and cracks is well demonstrated in the above data.

e) Single disc, 16.5 KV, 5000pf of Z5U, $BaTiO_3$, study:

One of the serious questions that has arisen is whether the barium titanate formulation called Z5U is suitable for large, thick discs such as 16.5 KV and above, capacitors of 5000pf. This Z5U $BaTiO_3$ formulation shows among other things a sharp drop-off with applied D.C. voltage in dielectric constant from about 6000 at low voltage to only about 1500 at field strengths of 50 volts/mil which is the average field strength which the manufacturers use for 16.5 KV discs. This formulation Z5U is ferroelectric, piezoelectric and has electrostriction at large field strengths. All of these phenomena are part and parcel of the large molecular polarization, and dipole and domain alignment that give rise to the extremely large dielectric constant at low voltages to begin with.

The partial discharge activity of the thick (above 15 KV) Z5U capacitors is quite high, even when the raw data has been corrected for the capacitance decrease with applied D.C. voltage. (The calibration of partial discharge equipment depends on the test sample capacitance, and is usually done at low voltage.) Table 21 shows some of the raw data on coated and uncoated 5000pf, 16.5 KV rated, Z5U disc capacitors, illustrating the capability of the ramp method to detect damage, such as small edge chips, on these capacitors when tested in Fluorinert liquid FC-40. Table 22 gives corrected summary data for another set of the same type of units, epoxy coated as well as bare, and the P.D. activity is still seen to be excessive. This gives warning of the high electric stresses and instabilities involved in a thick disc of the high dielectric constant formulation.

Table 21. 1984 Data: Raw P.D. Data, 1st Batch, Z5U, 5000pf, 16.5KV Rated
Barium Titanate
Calibr: 3.5→600 pc

V KV	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450pc					$\Sigma n_i q_i$ pc
Coated C_{28}																
			Starts at 6KV													
0→10	115	62	25	19	5	2	0	0	1						+436pc	Σ4650
10	31	18	9	3											+163	Σ897
10→17	5038	2757	1611	617	43	9									+226	Σ143,670
17	319	188	111	19											+108	Σ7787
17→25	9097	6589	2028	452	16	4	5	1	1						+356	Σ190,603
25	1502(1)		227	64	15	14	19	5	9	0	1	!	1	0	+503	Σ39,885
	106(2)	860	97	32	14	11	19	11	8	2	4	2	1	0	+518	Σ31,745
25→0	9	8	1													Σ126.9
Coated C_{38}																
			Starts at 4KV													
															+414	
0→10	186	122	40	17	4	1									+545pc	Σ5774.
10	38		16	4	1			(peaks at 42.5pc)							+156pc	Σ1264
10→17	4121	2387	1129	441	53	6	2	1	1						+371pc	Σ114,750
17	372	229	118	25												Σ8629
17→25	8330	6054	1814	440	18	2									+598	Σ172,500
															+610pc	
25	810(1)		145	28	14	GAP	2	6	6	3	3	4	1	1	+598pc	Σ24,931
	508(2)	308	46	25	17	2	6	4	6	6	6	6	2	2	+608	Σ23,754
25→0	14	13													+ 76pc	Σ201
Coated C_{40} Turn over																
			Starts at 5KV													
0→10	138	76	33	20	3	3	0	1	1						+373pc	Σ5460
10	30	18	8	4												Σ782
10→17	5289	3034	1621	590	37	3	3								+486pc	Σ146,390
17	491	339	122	29		(peaks at 23.3pc)									+102	Σ10,939

Table 21. (Continued)

V	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450 pc					$\Sigma n_i q_i$ pc
17→25	9358	6865	2086	397	7	200.3pc 3										Σ187,410
25	817(1)	601	171	37	5	181pc 3										Σ17,340
25→0	1	5.6pc						(peaks at 25.1pc)								Σ5.6
Coated C_{42}																
			Starts at 4.0KV													
0→10	253	164	44	28	10	0	2	2	0	2	(peaks at 41.9pc)					
10	15	10	3	1											+453pc	Σ8702
10→17	5692	3088	1772	757	67	3	3	1	(peaks at 23.3pc)						+169.7	Σ450.9
17	527	311	178	37											+493.	Σ166,940
17→25	11,094	7631	2716	711	27	4	3		1						+102pc	Σ13063
25	448(1)	334	93	20											+433pc	Σ247,032
															+552pc	Σ9435.
	258(2)	186	54	14	0	2									+391pc	
25→0	3	3													+437pc	Σ6274.
																Σ31.5
Coated C_{43}																
			Starts at 6KV													
0→10	97	50	31	8	4	0	3									
10	15	8	6												+306pc	Σ3743.
															+ 66pc	Σ402.
10→17	4707	2499	1510	645	44	7									+250pc	
				74.3pc											+510pc	Σ136,369
17	474	293	158	21												
																Σ10,779
17→25	8638	5840	2269	505	19	1	1			1					+493pc	
25	871(1)	591	157	44	18	11	5	5	11	9	7	6	3	4	+560pc	Σ193,000
				(peaks at 34.7)												Σ38,543
	597(2)	414	72	43	14	12	7	2	6	9	5	5	3	5	+604	Σ30,239

Table 21. (Continued)

V KV	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450 pc		$\Sigma n_i q_i$ pc
25	150(3)	35→6000pc: 2840,2459,2381,2093,1440,1160→857pc 14 counts											Σ58,827
		35→250, 78	250→500, 38	500→750pc 15 counts									
25→0	4	4											Σ63.2
Coated C_{44}													
			Starts at 5.5KV										
0→10	156	107	28	16	3	1						+419pc	Σ4606
10	45	29	11	5									Σ1123
10→17	5451	2981	1736 (peaks at 21.5pc)	673	53	3	1	0	2	1		+415pc	Σ156,878
17	529(1)	339	168	22									Σ12,068
	193(2)	121	60	12									Σ4,442
17→25	9407	6770	2182	440	12	2						+347pc	Σ194,070
25	874(1)	623	207	29	6	3	2	2	1			+365pc	Σ20,257
25→0	2	2											Σ22.
Coated C_{33}													
			Starts at 5.5KV										
0→10	26	20	2	0	2							+289pc, +480pc	Σ1331.
10	1	5.3pc											Σ5.3pc
10→17	70	53	11	3	1	1						+589	Σ2050
	Turn it over												
0→10	1755	1252	364	118	12	6	1	2					Σ38,891
10	107	79	16									+432pc, +1?4pc	Σ2220
10→17	7185	5180	1455	494	43	6	5	2					Σ154,808

Table 21. (Continued)

V KV	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450pc	$\Sigma n_i q_i$ pc
17	394(1)	275	88	29	1							+156pc Σ8,831
17→25	8723	6700	1543	440	27	6	2	2	1	0		+455, +464pc Σ166,587
25	749(1)	598	89	34	14	3	5	2	3			+326. +555pc Σ16,840
25→0	625(2) 20	506 14	65 6	25	13	6	2	4	1			+527pc, +489pc Σ15300. Σ362

Naked C_{15}

a) No HV before b) Looks terrible-chips, sharp solder, speck of something on cylinder

Starts at 2.5KV!

V KV	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450pc	$\Sigma n_i q_i$ pc
0→10 10	251 7	166 5	42 1	28 1	4	2	4	2	0	0	1	+539pc, +549pc Σ9064 Σ208.7
STOP 10→0 (50sec)	47	36	8	1								+221, +327pc Σ1313.

Naked C_9

a) No HV before b) Looks OK

Starts at 6.5KV

V KV	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450pc	$\Sigma n_i q_i$ pc
0→10 10	66 12	31 6	18 1	10 3	4	1	0	1				+432pc Σ2996 +191pc Σ613
10→17	2502	1110	831	492	53	9	4	1				+365pc, +392pc Σ89744
17	176(1)	99	42	21	5	2	1	2	1	0	1	+503pc, +541pc Σ7688
17→0	1	1										Σ11.2

Table 21. (Continued)

V KV	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450pc		$\Sigma n_i q_i$ pc
			Calib 3.5→600pc										
Naked C_8													
a) No HV		**b) Looks OK**											
			Starts at 5KV										
0→10	261	224	17	14	2	0	1	1				+540pc	Σ5000.
10	12	6	3	2								+477pc	Σ798.
10→17	2312	1076	751	434	40	10						+352pc	Σ78,690
17	150(1)	72	59	19									Σ4501
	85(2)	56	23	8									Σ2025
17→0	2	6.5	7.3										Σ13.8
Naked C_7													
a) No HV		**b) Big chip on one side, chip & solder peel on other**											
0→3	2371!	1495	423	307	97	30	10	3	3	1	2		Σ75,744
STOP													
Naked C_{21}													
a) No HV ??		**b) Chip at edge**											
			Starts at 3.5KV										
0→10	135	121	7	5	1							+182pc	Σ2059
10	0												
			Restarts at 13KV									+350pc.	
10→17	53	40	9	1	1							+608pc	Σ1517
17	9	6	3										Σ188.7
17→0	28	27										+343pc	Σ620.

Run again with polarity reversed

Table 21. (Continued)

V KV	ΣN	→25	→50	→100	→150	→200	→250	→300	→350	→400	→450pc		$\Sigma n_i q_i$ pc
Naked C_{22}													
a) No HV		b) Enormous Chip											
			Starts at 5KV			BURSTS!							
0→10	2080		259	30	1								
			45pc									+416pc	Σ31,494.
10	3	21	1										
STOP													Σ63.9
10→0	1	6.5pc											Σ6.5pc
Naked C_{25}			Starts at 2.5KV		already								
0→10	280	127	45	49	20	18	12	4	1	2		+407.	
10	901	753	134	13	0							+414pc	Σ17,892
after 75 sec												+167pc	Σ14,356
10→0	73	31	19	11	8	1	1						
50 sec												+326pc	Σ3487
		STOP!!											

Table 22. 1984 Data: Corrected P.D. Data
2nd batch, Z5U, 5000pf, 16.5KV, $BaTiO_3$

Due to capacitance change with voltage the raw data needs to be corrected.

0V Calibr.	5KV	10KV	17KV	20KV	25KV		
÷1	÷1.4	÷2.3	÷3.3	÷3.65	÷4.4	=	Correction

0→10	10→17	17→20	17→25		
÷1.8	÷2.8	÷3.5	÷3.9	=	Correction

Criteria

(1) Ramp to 17KV
(2) No more than 10,000→15,000pc
No pulse > 100pc
(3) Quiescent at 17KV
No more than 5x1.5pc/sec = 7.5pc/sec
No pulse > 25pc

Table 22. 1984 Data: Corrected P.D. Data
2nd batch, Z5U, 5000pf, 16.5KV, $BaTiO_3$

Coated #C46

Volts KV	CIV	ΣN	Corrected Highest Pulse	Corrected $\Sigma n_i q_i$ or $\Sigma n_i q_i/t$	
0→10	3KV	74	221pc	3150pc	
10		0	0	0	
10→17		155	211	2044pc	
17		609	28	25.68pc/sec→No	
17→25		660	143	3948pc	
25		3352	70	190.80pc/sec	

Coated #C47

Volts KV	CIV	ΣN	Corrected Highest Pulse	Corrected $\Sigma n_i q_i$ or $\Sigma n_i q_i/t$	
0→10	6KV	123	100.pc	1550pc	
10		134	50	8.32pc/sec	
10→17		4008	106	43,210	No
17	2953		136	469.70/sec	

Coated #C50

Volts KV	CIV	ΣN	Corrected Highest Pulse	Corrected $\Sigma n_i q_i$ or $\Sigma n_i q_i/t$	
0→10	4KV	163	231	3,490pc	
10		16	27	2.11pc/sec	
10→17		3348	80	36,214	No
17		948	35	46.90pc/sec	No
17→20		658	29.4	3430	
20		2105	25.7	71.90pc/sec	

Coated #C46

Volts KV	CIV	ΣN	Corrected Highest Pulse	Corrected $\Sigma n_i q_i$ or $\Sigma n_i q_i/t$	
0→10	3KV	504	215.	7317.pc	
10		18	47.8	1.50pc/sec	
10→17		3798	148.2	40,950pc	No
17		433	24.8	29.93pc/sec	
17→20		789	51.7	4920.pc	
20		974	29.5	62.21pc/sec	

Coated #C51

Volts KV	CIV	ΣN	Corrected Highest Pulse	Corrected $\Sigma n_i q_i$ or $\Sigma n_i q_i/t$	
0→10	2KV	488	333pc	9460pc	
10		55	59pc	4.64pc/sec	No
10→17		4133	91	40,350pc	No
17		1099	35.7	52.80pc/sec	
17→20		1264	143	6874pc	
20		1553	25.7	7180pc	

Table 22 (Continued)

Coated #52

Volts KV	CIV	ΣN	Corrected Highest single pulse	Corrected $\Sigma n_i q_i$ or $\Sigma n_i q_i/t$	
0→10	6KV	36	219pc	1257pc	
10		0	0		
10→17		121	186	1150	
17		980	21.8	27.40pc/sec	
17→10		139	154	794	
20		1366	22	34.10pc/sec	

Coated #C53

0→10	9KV	8	13	40	
10		23	8	0.93pc/sec	
10→17		32	37.5	191	
17		136	36.3	5.48pc/sec	No
17→20		37	25.4	141	
20		202	150	7.88pc/sec	

Coated #C54

0→10	4KV	64	288	1825	No
10		58	8.9	2.24pc/sec	
10→17		354	143	1910	
17		134	140	7.67pc/sec	No
17→20		59	66	302pc	
20		180	16.7	6.18pc/sec	

Coated #55

0→10	5KV	281	246pc	4722pc	
10		23	33pc	2.63pc/sec	
10→17		4441	157pc	48200pc	No
17		574	37pc	43.30pc/sec	No
17→20		1634	95pc	8530	
20		1151	34pc	76.50pc/sec	

Coated #56

0→10	2KV	897	329pc	12,130pc	
10		11	22pc	0.80pc/sec	
10→17		4739	192pc	47,680	No
17		573	34.2	44.10pc/sec	
17→20		1070	81	6630pc	
20(1)		1122	35.3	66.57pc/sec	
(2)		486	32.7	26.56pc/sec	

Table 22. (Continued)

Coated #57		Better			
Volts KV	CIV	ΣN	Corrected Highest pulse	Corrected $\Sigma n_i q_i$ or $\Sigma n_i q_i/t$	
0→10	4KV	62	62.2pc	655pc	
10		0	0	0	
10→17		56	17.8	289pc	
17		57	8.5	1.63pc/sec	
17→20		14	21.7	61.pc	
20		91	15.8	2.63pc	
Coated #58					
0→10	3KV	265	300.5	6,773pc	
10		0		0	No
10→17	BURSTS	861	207.8	5175pc	
17		50	42.4	2.57pc/sec	
17→20		57	62.8	413pc	
20		92	57.2	3.78pc/sec	
Inadvertantly - same polarity repeat					
0→10		0			
10		0			
10→17		15	15	57.8pc	
17		48	54.5	2.77pc/sec	No
17→20		10	13.4	34.8pc	
20		61	13.7	1.67pc/sec	
Coated #62				$\Sigma n_i q_i/t$	
0→10	8KV	3	28.3pc	35.5pc	
10		1			
10→17		36	101.4	409.pc	
17		58	14.8	1.70pc/sec	
17→20		37	54.5	138pc	
20		85	10.4	2.25pc/sec	
Reverse polarity on it					
0→10	2KV	129	293pc	3188.	
10		14	76	1.46pc/sec	
10→17		4092	129	44,152pc	No
17		515	45.4	38.60pc/sec	
17→20		912	49.1	5968	
20		840	24.9	51.50pc/sec	

Table 22. (Continued)

Coated #63

Volts KV	CIV	ΣN	Corrected Highest single pulse	Corrected $\Sigma n_i q_i$ or $\Sigma n_i q_i / t$	
0→10	5.5KV	182	305.pc	3320.pc	
10		30	46.	3.11pc/sec	
10→17		5347	200.7pc	60.828pc	No
17		531	71.5	39.10pc/sec	
17→20		1093	172.	7510pc	
20		1766	99.2	87.53pc/sec	

Coated #64 (Reverse tag from #63)

0→10	5KV	31	90.5pc	522.pc	
10		6	10.8pc	.126pc/sec	
10→17		89	171.pc	693pc	No
17		95	11.2	2.61pc/sec	
17→20		48	38.5	224.8pc	
20		278	36.7	7.10pc/sec	

Coated #61 (Reverse tag from #63)

0→10	3.5KV	231	116pc	2435.pc	
10		0		0	
10→17		145	78.9	1866.pc	
17		123	8.5	3.178pc/sec	
17→20		67	48.2	329.4pc	
20		429	66.5	12.74pc/sec	

Reverse the polarity

0→10	1KV	599	163pc	7541pc	
10		11	33.9pc	1.517pc/sec	
10→17		3384	121.4pc	36,878pc	No
17		334	28.8	24.42pc/sec	
17		520	53.4	3298pc	
20		703	44.1	42.29pc/sec	

Coated #60

			pc	pc of pc/sec	
0→10	7KV	151	339.pc	2668.pc	
10		10	35.2	1.317pc/sec	
10→17		4563	121.4	50,450pc	No
17		459	38.8	32.18pc/sec	
17→20		881	120.3	5725pc	
20		1135	28.	59.91pc/sec	

Table 22. (Continued)

Coated #65. Looking for highest pulses:

KV			Calib	Looking for highest pulses:		
0→10	7.5KV	128	→600	83.9pc	2,127pc	
10		19	→600	43	2.247pc/sec	
10→17		1529	→6000	181.7	13,648pc	No
17		460	→600	40.	40.20pc/sec	
17→20		69	→6000.	25.4	1088pc	
20		775	→600	47.1	53.20pc/sec	

Coated #68 Hi Voltage Cal Cap

			Cal	Highest pulse	Highest $\Sigma n_i q_i$	
0→10	5.5KV	193	at 0KV ÷1.8	284pc	3486.	
Adjusted cal at 10KV						
10		13		31pc	1.69pc/sec	Meas.
10→17		2790	÷1.5	386pc	28,800pc	
Adjusted cal at 17KV						
17		174		29pc	17.94pc/sec	Meas. NO
17→20		323	÷1.1	33.6pc	2668pc	
Adjusted cal at 20KV						
20		238		25pc	16.0pc/sec	Meas.

Experience, upon Life testing with these 5000pf, 16.5 KV Z5U capacitors and also earlier experience with some 37.5 KV units has shown a greater than usual tendency to fail catastrophically after only a few hours or days during the 80°C burn-in at rated or slightly above (10-20%) rated D.C. voltage. This is especially the case when the Life test is done on bare units in FC-40 Fluorinert liquid, not coated with the DK-90 fluidized bed epoxy coating.

This failure tendency has not been experienced with 1000pf, 10 KV single discs. It must be remembered that a 10 KV 1000pf disc is a more ideal shape than a 20 KV 1000pf unit. These get to be very far from the ideal large area, thin disc shape, and the edge effect becomes important. The electric field lines near the edges of the thick, blocky capacitor are not parallel to the cylindrical or thickness axis, but bulge outward. There is a component of the field lines perpendicular to the ceramic and medium-of-immersion interface. The boundary condition between two insulating media is that the normal components of the electric fields E at the interface are inversely proportional to the dielectric constants. If E inside the ceramic of dielectric constant 4000 is approximately 50 volts/mil, then even if its normal component to the cylindrical face is only small, such as 0.5 volts/mil, then immediately outside the ceramic the normal component would be of the order of 1000 volts/mil. The polarization charge on the cylindrical portion would be positive near the positive condensor plate and negative near the negative electrode. This can be seen from the analysis of Adams and Mautz, Figure 15, [24]. This makes the midplane parallel to and half-way between the electrode planes a transition plane with possibly more lattice dislocations and flaws than elsewhere and hence weaker breakdown strength. Beginning failure modes blow "wormholes" apparently diagonally from the negative condensor plate out through the middle region of the cylindrical surface whereas

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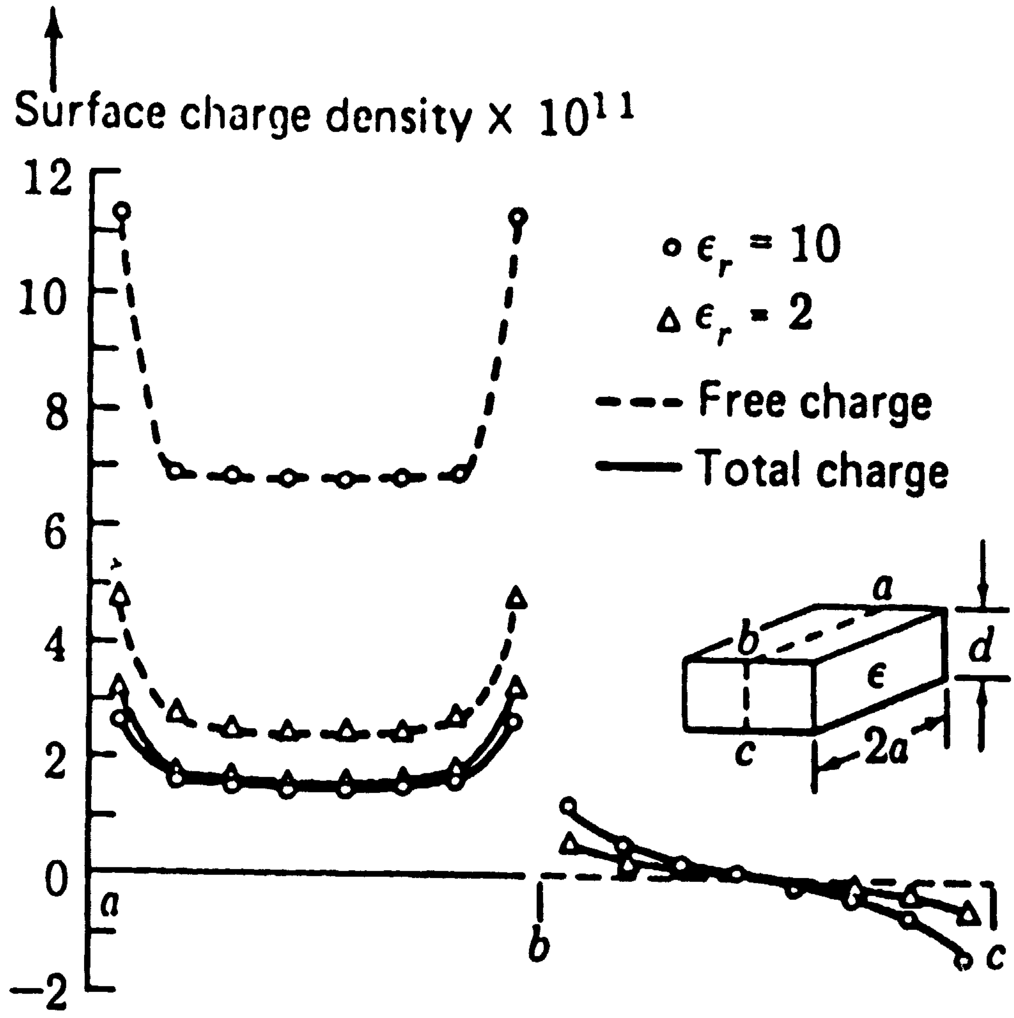

Figure 15. Charge distribution for a square parallel-plate dielectric-loaded capacitor. (After Adams and Mautz.)[24]

total failures have diagonal chunks of ceramic broken out from the negative plate to the mid-region on the cylindrical surface, with the rest of the breakdown path a carbon track along the cylindrical surface from the mid-region to the positive plate. The material in which the ceramic is embedded must be of very high dielectric strength, must adhere extremely well and should preferably be an immovable solid rather than a fluid.

It appears that above about 15 KV other types of capacitors should be considered rather than $BaTiO_3$ discs. These could be impregnated, reconstituted mica types or strontium titanate $SrTiO_3$ discs.

f) A Recent Pulse-Type Life Test on thick ceramic disc capacitors, $SrTiO_3$:

In collaboration with a contractor (General Electric Co.), initial and final D.C. P.D. measurements with a pulse-type Life test in between was carried out on some Strontium Titanate (rather than Barium Titanate) capacitors. These were thick discs, epoxy-coated, 2000pf. Six were 33 KV rated, six were 40 KV. Life test was carried out at 80°C in Silicone oil, with electric stressing consisting of 2×10^8 pulses of 20 KV height, 1 Khz repetition rate and of the order of 800 amperes peak discharge current. Several lessons were learned:

(1) Among the survivors more damage was evident to the 33 KV rated samples than to the 40 KV ones. Table 23 for the 33 KV #10 versus Table 24 for the 40 KV #2 illustrates this. The last column in the Tables is integrated summed total P.D. charge transferred during the 100 second dwell on each voltage plateau.

(2) The summary table 25 is for all samples. It gives integrated charge transfer on the ramps in picocoulombs. It is very striking that the 3 failures that occurred during the Life tests were those units that had the highest initial partial discharge, namely #'s 5 (40 KV rated), #12 and #13 (both 33 KV rated). This demonstrates again that on a statistical basis there is a correlation between high probability of failure and high initial partial discharge.

Table 23. Strontium Titanate Single Disc Capacitor #10, 2000pf, 33 KV Rated.

Calibr: Voltage	4.8→400pc ΣN	→20	→40	→60	→80	→100	→120	→140	→160	→180	→200	→220	→240	→260	→280	→300	→320	→340	→360	→380	→400	48→4000pc $\Sigma n_i q_i$
										BEFORE												
0→10	11	11																				Σ 128pc
10	5	5																				57
10→20	4	4																				34
20	0																					0
20→30	2	1	1																			39
30	0																					0
30→40	10	7	2		1																	199
40	6	4		1	1																	162
40→50	47								1													2083
50	163	121	27	3	3	1	2	1	1	0	1	2										3446
50→0	86	62	11	5	5	1	1	0	0	1												1850
													AFTER 10^8 DISCHARGES									
0→10	0																					
10	0																					
10→20	3	2	1																			Σ 36
20	63	63																				537
20→30	45	41	2	2																		523
30	240	222	13	5	1																	2530
30→40	166	141	20	4																		2219
40	765	684	59	14	5	1	1	00	0	1												8886
40→50	340	280	41	11	4	1	1	1													1	5279
50	1404	1116	132	47	17	13	6	1	3	1		1	1				1		1		1	+412pc, 424pc 23,597
50→0	23	17	6																			375

CLEARLY DAMAGED

Table 24. Strontium Titanate Single Disc Capacitor #2, 2000pf, 40 KV Rated.

BEFORE

Calibr. Voltage	ΣN (4.8→400pc)	→20	→40	→60	→80	→100	→120	→140	→160	→180	→200	→220	→240	→260	→280	→300	→320	→340	→360	→380	→400	$\Sigma n_i q_i$
0→10	2	2																				Σ 16
10	3	3																				27
10→20	2	2																				13
20	0																					0
20→30	2	2																				26
30	0																					0
30→40	1	0	1																			30
40	1	0	1																			21
40→50	15	14		60																		237
50	107	←99→		6	2																	1802
50→60	77	←59→		10	6		1	1														921
60	138	←134→		1	2	1																2561pc
60→0	81																					1871pc

AFTER 10^8 DISCHARGES

Only slightly worse.

Calibr. Voltage	ΣN	→20	→40	→60	→80	→100	→120	→140	→160	→180	→200	→220	→240	→260	→280	→300	→320	→340	→360	→380	→400	$\Sigma n_i q_i$
0→10	0																					
10	0																					
10→20	0																					
20	0																					
20→30	2	1	1																			Σ 41pc
30	1	1																				8
30→40	12	10	2																			150
40	8	8																				72
40→50	49	35	10	2	0	1				1												944
50	146	132	13	1																		1756
50→60	134	91	21	9	4	1		2	1	1	2		1							1		3816
60	399	279	84	25	4	2	3	1		1												7250pc
60→0	11	4	3	3	1	2								1								610

Table 25a. Before Life Test on Ramps.
(Each column is sum of its ramp and preceding column). Σpc.

SN	Rating KV	0→10 KV	0→20 KV	0→30 KV	0→40 KV	0→50 KV	0→60 KV
1	40	0	16.4	52.4	1031	2328	4288
2	40	12.9	38.5	68.5	305	1226	3097
3	40	35.2	70.6	90.3	175	3623	23,851
4	40	20.5	53.5	94.7	139	720	7117
5*	40	0	0	480.	4022		
6	40	0	0	666.	3412		
10	33	98	132	161	360	2443	
11	33	0	40	880	3513		
12*	33	0	0	1000	15,039		
13*	33	0	66	1165	5331		
14	33	0	0	733	3373		
15	33	0	40	840	4152		

*Later failed, #5, #12 during Life test; #13 on post-Life P.D. test.

Table 25b. After Life Test on Ramps.
(Each column is the sum of its ramp and preceding column).

SN	Rating	0→10	0→20	0→30	0→40	0→50	0→60	
1	40	0	39.6	149.6	934.6	4502	15,749	Worse
2	40	0	0	40.8	190.8	1134	4950	Worse on last ramp
3	40	0	0	53	199	414	1408	Better
4	40	0	0	43.6	266	1069	2723	Better
5*								
6	40	0	Worse 34.8	513.8	2181.8	5969	14,094	Worse early on, about the same later.
10	33	0	36	559.6	2778.6	8057.6		Worse
11	33	0	95.6	292.4	1540	5628		Somewhat better
12*	33							
13*	33	6	42.8	712.8	2400	BREAKDOWN		
14	33	0	43.2	428.8	3391	9289		Worse
15	33	0	20	449	2122	3318		Better

It must be realized that 2×10^8 pulses of 20 KV height is an extremely stressful test, and if the Life test had been carried out at steady D.C. voltage, there probably would not have been any failures. Such a D.C. Life test is planned on some of these $SrTiO_3$ capacitors in the near future.

CONCLUSION:

Acceptance/Rejection criteria:

D.C. partial discharge testing is a sensitive test of insulation integrity and it is non-damaging. The test article is only exposed to a slow D.C. voltage ramp to the voltage which it is supposed to see in service or somewhat above. There are no fast frequent stressful polarity reversals with steep voltage rises such as in A.C. partial discharge testing. The D.C. P.D. test does not shorten service life.

From the many different material and capacitor samples tested so far some acceptance/ rejection criteria can emerge. The ideal situation would be, of course, not to have any partial discharges at the working voltage and up to it, on the act of ramping up. This is precisely what the electric power industry aims for in its component testing and use. For D.C. parts and assemblies for Space use this would result in some very large-sized, heavy, unwieldy parts. The task then, is to judge from our experience, how much P.D. one can reliably get away with, for D.C. service. To state such numerical cr'teria is, of course, risky business, and the author reserves the right to modify these criteria as experience increases. The reader must also understand that partial discharges precede catastrophic breakdown only if part of the electrode to electrode path is interrupted by solid or liquid insulation. Purely gaseous breakdown between metallic electrodes is not preceded or heralded by small partial discharges.

Our acceptance/rejection criteria consist of several conditions–all must be fullfilled for acceptance. These criteria were arrived at based mostly on 1000pf capacitor samples and their performance.

I.) On the quiescent plateau of rated voltage there should be, after a 2 minute wait

1.) No more than 1.5 pc/second average corona current, that is, no more than 150pc integrated pulse charge transfer in 100 seconds of observation time.

2.) No more than 25pc in any single given pulse on the rated voltage plateau.

II.) On the ramping to rated voltage, doing this in 40 seconds time (equivalent approximately to four 10 second quarterly ramps):

3.) There should be no more than about 1500-2000pc total integrated pulse charge transfer for ceramics, and no more than about 1000pc for potting resins.

4.) There should be no more than 100pc in any single pulse.

III.) A sample of larger capacitance should be allowed to have a larger number of discharges, but not larger single pulses. Should this increase vary directly with capacitance C or with $\sqrt{C}$? It is felt that items 1.) and 3.) should be allowed to increase with $\sqrt{C}$ because much of the P.D. comes from the periphery of the electrodes rather than uniformly over the whole area.

IV.) Any samples that show multiple corona bursts or that show discharges at preferred picocoulomb values or preferred peak distribution, should be rejected.

V.) A test sample that has had previous high voltage on it should be ted twice, once at the same as previous polarity and then reversed. This is so that ferroelectric samples will not mistakenly be considered as discharge-free, when in fact the previous polarization is internally counteracting the externally applied field.

VI.) The operator must have a good understanding of P.D. or corona measurements, both D.C. and A.C. and understand the difference; also the calibration procedure must be mastered and taken very seriously, since the quantitative measurement and criteria of D.C. partial discharge depends on correct calibration of the equipment at the start of each measurement.

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APPENDIX I.

Simple Models of Gas ... *in a Dielectric for D.C. and for A.C. Applied Voltage.*

How does the "terminal corona-pulse voltage" or better, how does the apparent terminal charge-content of the pulse indicate what is really going on in an internal cavity? In other words, how do the relative sizes of cavity and dielectric thickness influence what magnitude of charge appears at the test sample terminals, corresponding to what goes on in the void? One can try to answer this by modeling the cavity.

A) At quiescient D.C. voltage:

Figure 3b shows the equivalent circuit of a corona-causing cavity in a slab of dielectric under D.C. conditions.

Here C_a, C_b and C_c represent the capacitances of the dielectric free from cavities, the dielectric in series with the cavity, and the cavity itself respectively. Similar subscript letters are used with the parallel resistances R_a, R_b and R_c.

At the true discharge inception voltage which is the lowest voltage at which discharges can occur in the void according to Paschen's curve, the time between successive discharges is extremely long, and so the discharge inception voltage is difficult to observe. As the applied voltage is increased to where one observes a few countable pulses per minute, the applied D.C. voltage V is already above the inception voltage V_i.

The capitalized voltages V and V_i refer here to the externally applied voltages that correspond to the voltages v and v_i across the actual internal cavity and $V = nV_i$; $n = 1, 2, 3 \ldots$

An analysis that is based on the above ideas predicts the following relationships for D.C. applied voltages [1, 25].

At the discharge inception voltage, the apparent discharge magnitude q is given by

$$q_{P.D.} = \left[C_a + \frac{C_b\,C_c}{C_b + C_c}\right] \cdot \frac{C_b}{C_a + C_b} \cdot \frac{R_c}{R_b + R_c} \cdot V_i \qquad (1)$$

Hence the energy W dissipated by the discharge is

$$W = \tfrac{1}{2}qV_i \frac{R_c}{R_b + R_c} \cdot \frac{C_b + C_c}{C_b} = \tfrac{1}{2}qV_i\,\gamma \qquad (2)$$

where

$$\gamma = \frac{R_c}{R_b + R_c} \cdot \frac{C_b + C_c}{C_b}$$

and is slightly larger than 1. Since one often works at $V = nV_i$, the energy dissipated per pulse can be written

$$W = \tfrac{1}{2}q\frac{V}{n}\gamma \qquad (3)$$

but is still the same as at discharge inception voltage. The number of discharges occurring per unit time or the discharge repetition rate, f, is

$$f = -\varphi/\gamma\epsilon\epsilon_o \ \mathrm{Ln}\ (1 - \frac{1}{n});\ \text{if } n \gg 1,\ \text{then } f \cong n\varphi/\gamma\epsilon\epsilon_o \qquad (4)$$

where φ is the conductivity, ϵ the relative permittivity or dielectric constant of insulating material and ϵ_o the permittivity of free space.

Several insights can be gained from these equations:

(a) To quantity $\varphi/\epsilon\epsilon_o$ is the cogent material property factor for D.C. partial discharge. It represents the inverse of the time constant for charge distribution in the dielectric material [3]. It to a large degree determines the frequency of P.D. pulses for the quiescent D. C. case of applied voltage, equation (4).

(b) It is seen from equation (1) that the relative magnitudes of C_c, C_a, and especially C_b, which is the capacitance of the dielectric in series with the cavity, greatly influence the amount of apparent *charge content q* in a given pulse, that appears at the output terminals of the test sample. In other words, even if the test samples are similar in their gross features and even if the circuit sensitivity is the same, then one should still expect different charge content of the output pulses depending on the relative size of the flaw and the thickness of the dielectric that it is buried in.

(c) Another feature emerges from equation (4). It is seen that the repetition rate varies directly with the conductivity of the insulating material. But the conduction process in high polymers is not a simple process: Conductivity decreases with time, exponentially, after application of voltage. Theoretically the conductivity in polymers is influenced by trapping of the few free charge carriers and of the injected electrons, at shallow and at deep traps. This is a time-dependent process. Also space-charge effects enter in as charge is injected into the polymer, and interface at the electrodes add to the complications. Thus immediately after application of D.C. voltage the discharge frequently drops off with time.

(d) The prediction from equation (3), that there simply are more and more pulses as the voltage is raised, all of the same charge and energy content has not been found to be true, in general, in actual experiments on D.C. Partial Discharge conducted by the author: as D.C. voltage is increased the percentage of more energetic pulses also increases. This probably is due to the presence in a given test sample of many flaws and tiny voids. So perhaps, as voltage is increased, discharges are energized in more and more sites of imperfection, rather than all coming from one site at ever-increasing repetition rate.

(B) For A.C. applied voltage: [8]

Figure 3a is applicable under A.C. applied voltage conditions or upon the ramp from one voltage level to another. The division of applied voltage between void and intact dielectric is capacitative here rather than the resistive division of the D.C. case. In a pancake void with axis parallel to the electric field, the electric field within the void is k times the field within the dielectric, where k is the dielectric constant (ϵ = k). The fringing fields and a possible field discontinuity are ignored here, and in the regions X, Y, Z in the Figure 3a the following is the case:

In the regions X and Z the capacitance per unit area is

$$C_a = k\epsilon_o/t \tag{5}$$

where t is the thickness.

In region Y, the capacitance of the void C_c and of the remaining material C_b, per unit area is

$$C_c = \epsilon_o/d \quad C_b = k\epsilon_o/(t - d) \tag{6}$$

where d is the thickness of the void. The capacitance of the entire portion Y, per unit area

$$C_Y = \frac{k\epsilon_o}{t + d(k - 1)} \tag{7}$$

The electric fields in portion Y, *for the capacitor plates maintained at voltage V,* are, for the field within and without the void

$$E_{in} = k\ E_{out} \quad E_{out} = V/(t + d(k - 1)\ ) \tag{8}$$

The fields in part X and Z are V/t.

It is now possible to find the free charge distribution in the capacitor plates. This will not be uniform: In the regions of no void, the charge per unit area is

$$Q = (k\epsilon_o/t) \cdot V \tag{9}$$

In the section with the void the distribution is

$$Q = (k\epsilon_o/[t(1 + n(k - 1)\ )]) \cdot V \tag{10}$$

where $n = d/t$.

When the void discharges to an effective zero field in the void, then the change in the free charge observed in the capacitor plates is, *per unit area*

$$\Delta Q_f = \frac{k\epsilon_o V}{t} \left[1 - \frac{1}{1 + n(k - 1)} \right] \quad (11)$$

The corresponding charge transfer within the void is then *per unit area*

$$Q = k\epsilon_o V/(t - d) \quad (12)$$

It is useful now to make a calculation as to what order of magnitude of charge change to expect for a particular geometry.

Assume t = 3mm. Assume a discharge inception voltage, at atmospheric pressure, across a cylindrical void 2 mm in diameter and 1 mm deep, of 20,000 volts, V, applied field. This is not unreasonable, as seen from the several Paschen curves enclosed here. If one now substitues in equation (11), one obtains if one uses $k = 4$

$$\Delta Q_f = \frac{4 \times 8.8 \times 10^{-12} \times 20{,}000}{0.003} \left[1 - \frac{1}{1 + \frac{1}{2} \times 3}\right] \times \frac{\Pi\ 10^{-6} \times 4}{4}$$

$$= 400\text{pc}$$

This amounts to a change in free charge of about 400 *picocoulombs.* The result depends very sensitively on the relative void to dielectric size, of course. The result is of the order of magnitude of charge measured for the material samples with pillbox voids.

APPENDIX II.

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TABLE 2: MATERIALS PROPERTIES - ELECTRICAL

TARGET PROPERTIES			ARC RESISTANCE	DIELECTRIC CONSTANT < 6.0	DISSIPATION FACTOR	DIELECTRIC STRENGTH V/MIL	RESISTIVITY SURFACE OHM > 10^{12}	RESISTIVITY VOLUME OHM - CM > 10^{12}	TRANSPARENCY COLOR	MOISTURE ABSORPTION	REVERSION RESISTANCE YES	WATER PERMEABILITY $\frac{g}{hr\text{-}cm}$	FUNGUS RESISTANCE Non-Nutrient	SPECIFIC GRAVITY
FLEXIBLE MATERIALS														
SILICONES														
UNFILLED														
SYLGARD	182	DC							Cl	.1%				1.05
SYLGARD	184	DC							Cl	.1%				1.05
SYLGARD	186	DC		3.0 100 KHz	.001 100 MHz	575	$7x10^{16}$	$2.4x10^{13}$	Cl	.15%	YES	$1.0x10^{-7}$	NON NUTR	1.12
RTV	602	GE		3.0 100 KHz	.0012 100 KHz	500		$1x10^{14}$	Cl	.08%	YES		NON NUTR	1.004
RTV	615	GE		3.0 1 KHz	.01 1 KHz	500		$4.5x10^{13}$	Cl	.05%	YES		NON NUTR	1.02
RTV	619	GE		3.0 1 KHz	.001 1 KHz	500		$1x10^{15}$	Cl					.97
FILLED														
SILASTIC	E (93-072)	DC							OP-WH					1.12
SILASTIC	881	DC		2.9 1 MHz		550		$1x10^{14}$	OP	.4%				1.13
CHEM SEAL	3000	CS	50 sec	5.0 1 MHz		300		$1x10^{13}$	OP-RED		NO			1.47
DC	3116	DC	90 sec	5.5 10 KHz	.03 10 KHz	500		$1x10^{13}$	OP-WHITE	.4%				1.17
SYLGARD	170	DC		3.1 100 KHz	.002 100 KHz	450		$1x10^{15}$	OP BLK	.1%				1.38
SYLGARD	96-082	DC		2.99 100 KHz	.002 100 KHz	500	$5x10^{15}$	$5x10^{14}$	OP BLK					1.21
GELS														
DC	51	DC		3.0 100 KHz	.0001 100 KHz	500		$1x10^{11}$	Cl					.97
DC	F-1-3523	DC		2.7 100 KHz	.0001 100 KHz	450		$1x10^{14}$	Cl					.97
URETHANES														
FILLED														
CONATHANE	EN-2523	CON	130 sec	3.5 [illegible]MHz	.012 1MHz	630	2.[illegible]$x10^{12}$	$3.4x10^{13}$	OP TAN	.14			NON NUTR	1.44

MATERIALS PROPERTIES

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TABLE 2: MATERIALS PROPERTIES - ELECTRICAL (Con't.)

SEMI-FLEXIBLE MATERIALS			ARC RESISTANCE	DIELECTRIC CONSTANT	DISSIPATION FACTOR	DIELECTRIC STRENGTH V/Mil	RESISTIVITY SURFACE OHM	RESISTIVITY VOLUME OHM-CM	TRANSPARENCY COLOR	MOISTURE ABSORPTION	WATER PERMEABILITY	REVERSION RESISTANCE	FUNGUS RESISTANCE	SPECIFIC GRAVITY
TARGET PROPERTIES				≤ 6.0			$\geq 10^{12}$	$\geq 10^{12}$			9 hr-cm	YES	NON NUTRIENT	
URETHANES														
UNFILLED														
PR	1527-M	PRC	194 sec	4.1 1 MHz	.09 1 MHz	310		$2.5x10^{11}$	OP Amb - Blk			YES	non nutr	1.06
[illegible]	[illegible]	PRC		4.[illegible]	.35 1 MHz	[illegible]		$1.51x10^{13}$	Cl Straw			NO		1.04
PR	1578	PRC							Cl Amber					1.07
PR	1592	PRC	150 sec	4.6 1 MHz	.06 1 MHz	300	$1x10^{13}$	$1x10^{12}$	Cl Dk Amber	2.4%		YES	non nutr	1.08
SCOTCHCAST	221	3M		3.0 100 KHz	.05 100 KHz	340		$1.3x10^{13}$	CL Amb	.23%		NO		1.06
CONATHANE	EN-2522	CON	160 sec	3.3 1 MHz	.016 1 MHz	610	$1.0x10^{13}$	$1.2x10^{1?}$	CL DK AMBER	.22%			non nutr	1.1
SOLITHANE	113	THI		2.55 1 MHz	.012 1 MHz	400	$1.5x10^{15}$	$3.8x10^{13}$	CL Amb	.23%		NO		1.04
FILLED														
CONATHANE	EN-2521	CON	130 sec	3.7 1 MHz	.016 1 MHz	650	$2.0x10^{13}$	$1.2x10^{14}$	OP - Tan	.19%			non nutr	1.53
SOLITHANE/ CABOSIL	113	THI												
ISOCHEMREZ	468	ISO		4.61 100 KHz	.025 100 KHz	450		$1x10^{13}$	Cl	.10%				1.15
POLYSULFIDES														
FILLED														
PROSEAL	727	PRC	25 sec	9.5 1 MHz	.03 1 MHz		$1x10^{12}$	$1x10^{11}$	OP - Lt Brn				non nutr	
PR	1201 Q	PRC	50 sec	9.3 1 MHz	.024 1 MHz	220	$1.2x10^{12}$	$1.9x10^{11}$	OP - Red-Brn					
GC	1300	GRO	61 sec	9.8 1 MHz	.014 1 MHz	262	$1.2x10^{12}$	$8.7x10^{11}$	OP - Brn					
POLYBUTADIENES														
FILLED														
CB	1109	DOL		2.91 - 1 MHz	.020 1 MHz	665	$3.06x10^{14}$	$1.78x10^{15}$	OP - Blk					1.2
Poly bd	2-011	ARCO		2.94 - 1 MHz	.021 - 1 MHz		$3.06x10^{14}$	$1.75x10^{15}$						
PHENOLIC - OIL														
FILLED														
C	1525A	VIK				1260			Cl - Lt Brn	.16%				
C	1525F-35	VIK				1000			OP - Blk	.16%				
C	1525G-05	VIK				1000			OP - Tan	.16%				

MATERIALS PROPERTIES LITERATURE

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TABLE 2: MATERIALS PROPERTIES - ELECTRICAL (Con't.)

			ARC RESISTANCE	DIELECTRIC CONSTANT	DISSIPATION FACTOR	DIELECTRIC STRENGTH V/mil	SURFACE OHMS	VOLUME OHM-CM	TRANSPARENCY COLOR	MOISTURE ABSORPTION	WATER PERMEABILITY	REVERSION RESISTANCE	FUNGUS RESISTANCE NON-NUTRIENT	SPECIFIC GRAVITY
RIGID MATERIALS											g/hr-cm	YES		
TARGET PROPERTIES				≤ 6.0			$\geq 10^{12}$	$\geq 10^{12}$						
EPOXIES														
UNFILLED														
SCOTCHCAST	5	3M		3.9 100 Hz	08 [illegible]	325		$1x10^{14}$	Cl	.2%				
SCOTCHCAST	8	3M		5.0 100 Hz	.098 [illegible]	350		$3.8x10^{14}$	Cl	1.2%				1.15
ISOCHEMREZ	460	ISO		4.15 100 KHz	.018 [illegible]	[illegible]20		$1x10^{14}$	Cl	.11%				
SCOTCHCAST	280	3M		366 100 Hz	.012 [illegible]	375				.52%			non nutr	1.15
STYCAST	1264	EC		3.5 1 MHz	.028 [illegible]	422	9 $1x10^{14}$	$5.1x10^{13}$	Cl - Blue	.37%				1.05
ISOCHEMREZ	402-LV	ISO		4.0 100 KHz	.035 100 [illegible]	410		$1x10^{13}$	OP - Blk	.11%				1.18
CONAPOXY	IN-1145	CON		3.7 119 Hz	.004 1 MHz			$7.1x10^{12}$	Cl - Amb					1.14
NORDBAK	1-0012	REX	45 sec	[illegible].6 1 KHz	.034 1 KHz	390		$3.9x10^{14}$	Cl - Amb					1.07
NORDBAK	1-00[illegible]	REX	30 sec	3.5 1 KHz	.041 1kHz			$4.4x10^{15}$	Cl - Amb					
FILLED														
SCOTCHCAST	281	3M		3.56 100 Hz	.054 100 Hz	375		$1x10^{15}$	OP - Brn	.32%				
PR	2200	FRI		4.2 60 Hz	.018 60 Hz	480		$1.5x10^{16}$	OP - Blk					1.45
POR	1322	DOL				450	> $1x10^{6}$							1.37
ISOCHEMREZ	402AP	ISO		4.2 100 KHz	.005 100 KHz	4[illegible]		$1x10^{4}$	OP - Blk	.09%				1.38
ISOCHEMREZ	405NSO	ISO		4.4 100 KHz	.010 100 KHz	4[illegible]		$1x10^{16}$	OP - Blk	.09%				1.55
SCOTCHCAST	9	3M		5.34 100 Hz	.061 100 Hz	350		$4.8x10^{14}$	OP - Brn	.67%				
STYCAST	1090	EC		3.1 1 MHz	.01 1 MHz	375		$3.6x10^{13}$	OP - Blk	.23%				.81
STYCAST	1090-1	EC		2.9 1 MHz	.01 1 MHz	375		$1x10^{13}$	OP - Blk	.52%				.79
STYCAST	2651 MMFR	EC		4.2 10 GHz	.02 10 GHz	440		$5.6x10^{13}$	OP - Blk	.06%	$1.2x10^{-5}$			1.62
STYCAST	2850 FT	EC		5.9 1 MHz	.02 1 MHz	380		$4.3x10^{10}$	OP - Blk	.08%			non nutr	2.3
HYSOL	C-68	HY		4.24 10 KHz	.006 10 KHz	750		$2.1x10^{11}$	OP - Gry	.002%				
SCOTCHCAST	XR-5068	3M(Syntactic Foam)		2.0 1 MHz	08 1 MHz			$1x10^{12}$	OP - LT Orange					.21
SCOTCHCAST	247	3M	68 sec	4.3 1 KHz	.03 1 KHz	400	$1x10^{12}$	$4x10^{13}$	OP - Brn	.11%	$2.0x10^{-5}$			1.55
RIPLEY RESIN	404-XD-10	RIP		4.03 1 KHz	.048 1 KHz	610			OP - Blue					
RIPLEY RESIN	494-XD-10	RIP		4.03 1 KHz	.048 1 KHz	610			OP - Tan					
RIPLEY RESIN	2466-MA-1	RIP		2.4 1 MHz	.008 1MHz	580				.035%				
NORDBAK	1-0050	REX	122 sec	3.9 1 KHz	.006 1 KHz			$4.7x10^{15}$	OP - Blk					1.6
NORDBAK	1-0061	REX	70 sec	4.1 1 KHz	.0049 1 KHz			$6.8x10^{14}$	OP - Blk					1.29
HYSOL	ES0264	HY	144 sec	4.2 100 KHz	.034 100 KHz		$8x10^{13}$	$1x10^{14}$		.22%				
HYSOL	977-87	HY	123 sec	3.53 100 KHz	.0086 100 KHz	567		$1.06x10^{16}$	OP - Tan					
POLYESTER														
UNFILLED														
STYPOL	40-1021	FRE								.22%				
STYPOL	40-1124	FRE	92 sec	3.03 1 MHz	.014 1 MHz	540 V/min Step				.32%				1.068
STYPOL	40-1037	FRE												
FILLED														
STYPOL	40-1602	FRE							OP - Blk	.27%				1.44

TABLE 2: MATERIALS PROPERTIES - MECHANICAL

FLEXIBLE MATERIALS	TARGET PROPERTIES		THERMAL SHOCK RESISTANCE	SHRINKAGE V=VOLUME L=LINEAR	AGE SHRINKAGE	HARDNESS A-D = SHORE	IMPACT RESISTANCE	ELONGATION	SERVICE TEMPERATURE	HEAT DISTORTION TEMPERATURE	COEFFICIENT THERMAL EXPANSION	THERMAL CONDUCTIVITY
									$-55^{\circ}C$-$+105^{\circ}C$			
SILICONES												
UNFILLED												
SYLGARD	182	DC	Pass 10 MIL-1-16923			40A		100%	$-65^{\circ}C+200^{\circ}C$			3.5×10^{-4} cal-cm
SYLGARD	184	DC	Pass 10 MIL-1-16923			35A		100%	$-65^{\circ}C+200^{\circ}C$			3.5×10^{-4} cal-cm
SYLGARD	186	DC		0%V	.44%V	40A		480%	$-65^{\circ}F+480^{\circ}F$		$1.6\times10^{-4}/^{\circ}F$	1.3 BTU-in
RTV	602	GE	5- $-85^{\circ}F$	.60%V	1.11%V	15A			$-90^{\circ}F+300^{\circ}F$		$1.8\times10^{-4}/^{\circ}F$	1.07 BTU-in
			+0 $257^{\circ}F$	1.21%V	.98%V	25A		150%	$-80^{\circ}F+390^{\circ}F$		$1.54\times10^{-4}/^{\circ}F$	1.23 BTU-in
RTV	615	GE										
RTV	619	GE										
FILLED												
SILASTIC	E (93-072)	DC				30A		325%				
SILASTIC	881	DC		.7%L		35A			$-67^{\circ}F+482^{\circ}F$			
CHEM SEAL	3808	CS		5%V		50A						
DC	3116	DC	Pass 10- MIL-1-16923	.4%L		40A		225%	$-65^{\circ}C+250^{\circ}C$			5.2×10^{-5} cal-cm
SYLGARD	170	DC	Pass MIL-1-16923			55A		150%			$8\times10^{-4}/^{\circ}C$	
SYLGARD	96-082	DC				35A		150%	$-65^{\circ}C+250^{\circ}C$			
GELS												
DC	51	DC							$150^{\circ}C$		1% per $10^{\circ}C$	7×10^{-4} cal-cm
DC	F-1-3523	DC							$-65^{\circ}C$		1% per $10^{\circ}C$	
URETHANES												
FILLED												
CONATHANE	EN-2523	CON	Pass 10- -65 to $+190^{\circ}C$	.59% L		55-D		50%	$-55^{\circ}C$-$+130^{\circ}C$		$15\times10^{-5}/^{\circ}C$	4.5×10^{-4} cal-cm

MATERIALS PROPERTIES
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TABLE 2: MATERIALS PROPERTIES - MECHANICAL (Con't.)

TARGET PROPERTIES			MODULUS TENSILE 500,000 psi	MODULUS FLEXURAL 450,000 psi	MODULUS COMPRESSIVE 425,000 psi	STRENGTH TENSILE psi	STRENGTH FLEXURAL psi	STRENGTH COMPRESSIVE psi	VISCOSITY CPS
FLEXIBLE MATERIALS									
SILICONES									
UNFILLED									
SYLGARD	182	DC				900			5,500
SYLGARD	184	DC				900			5,500
SYLGARD	186	DC				800			60,000
RTV	602	GE							1,500
RTV	615	GE				900			3,500
RTV	619	GE							500
FILLED									
SILASTIC	E (93-072)	DC				750			65,000
SILASTIC	881	DC				300			
CHEM SEAL	3808	CS				650			70,000
RTV	3116	DC				375			50,000
SYLGARD	170	DC				500			3,000
SYLGARD	95-082	DC				250			1,500
GELS									
DC	51	DC							600 CSTKS
DC	F-1-3523	DC							500 CSTKS
URETHANES									
FILLED									
CONATHANE	EN-2523	CON				1600			2,800

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TABLE 2: MATERIALS PROPERTIES - MECHANICAL (Con't.)

SEMI-FLEXIBLE MATERIALS	TARGET PROPERTIES		THERMAL SHOCK RESISTANCE	SHRINKAGE V=VOLUME L=LINEAR	AGE SHRINKAGE	HARDNESS SHORE	IMPACT RESISTANCE	ELONGATION	SERVICE TEMPERATURE -55°C to +105°C	HEAT DISTORTION TEMPERATURE	COEFFICIENT THERMAL EXPANSION	THERMAL CONDUCTIVITY
URETHANES												
UNFILLED												
PR	1527-M	PRC		2.5%V		82 - A		563%	-70^oF $+300^oF$		$1.0 \times 10^{-4}/^oF$	
PR	1546	PRC				50 - A		100%	-65^oF $+300^oF$		$1.35 \times 10^{-4}/^oF$	1.025 BTU-in
PR	1578	PRC				80 - A		600%	-320^oF			
PR	1592	PRC				85 - A		425%				
SCOTCHCAST	221	3M	10~ -65^oF $+265^oF$	1.7%V	.18%V	60 - A	23.4 ft-in MIL-I-16923	65%	266^oF		$1.17 \times 10^{-4}/^oF$	1.22 BTU-in
CONATHANE	EN-2522	CON	10 -65^oC $+130^oC$	.91%L		55 - D		80%	-55^oC-$+190^oC$		$21 \times 10^{-5}/^oC$	2.6×10^{-4}Cal-cm
SOLITHANE	113	THI		4.%V		60 - A	107 ft-in	100%			$5.4 \times 10^{-5}/^oF$	
FILLED												
CONATHANE	EN-2521	CON	PASS 10 ~ -65 + 130^oC	.71%L		72 - D		40%	-55-$+130^oC$		$16.10^{-5}/^oC$	6.5×10^{-4}Cal-cm
SCLITHANE/CABOSIL	113	THI				60 - A			-40^oF-$+200^oF$			
ISOCHEMREZ	468	ISO		.40%L		74 - D			-60^oC $+200^oC$		$7.1 \times 10^{-5}/^oC$	6.3×10^{-4}Cal-cm
POLYSULFIDES												
FILLED												
PROSEAL	727	PRC		12%V		50 - A						
PR	1201	PRC		12%V		40 - A			-70^oF-$+225^oF$			
GC	1300	GRO				45 - A			-70^oF			
POLYBUTADIENES												
FILLED												
CB	1109	DOL	-72^oC FLEX	.021%		45 - A		180%				
POLY bd	2-011	ARCO						285%				
PHENOLIC - OIL												
FILLED												
C-	1525A	VIK		.2%					-85^oF + 400^oF			
C	1525F-35	VIK		.15%		30 - A_2			-85^oF + 400^oF			
C	1525G-45	VIK		.15%					-85^oF + 400^oF			

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TABLE 2: MATERIALS PROPERTIES - MECHANICAL (Con't.)

SEMI-FLEXIBLE MATERIALS			MODULUS TENSILE	MODULUS FLEXURAL	MODULUS COMPRESSIVE	STRENGTH TENSILE	STRENGTH FLEXURAL	STRENGTH COMPRESSIVE	VISCOSITY cps
URETHANES	TARGET PROPERTIES		500,000 psi	450,000 psi	425,000 psi	psi	psi	psi	
UNFILLED									
PR	1527-M	PRC				2,360			19,500
PR	1546	PRC				1,000			15,000
PR	1578	PRC	500 (100%)			5,000			37,000
PR	1592	PRC	600 (100%)			6,000			20,000
SCOTCHCAST	221	319				225			900
CONATHANE	EN-2522	CON				2,700			420
SOLITHANE	113	THI				400			4,000
FILLED									
CONATHANE	EN-2521	CON				1,600			4,000
SOLITHANE/CABOSIL	113	THI							
ISOCHEMREZ	468	ISO				5,220		6,645	800
POLYSULFIDES									
FILLED									
PROSEAL	727	PRC							50,000
PR	1201	PRC							55,000
GC	1300	GRO							55,000
POLYBUTADIENES									
FILLED									
CB	1109	DOL				1,260			8,400
POL. bd	2-011	ARCO	365 (100%)			820			
PHENOLIC - OIL									
FILLED									
C-	1525A	VIK							3,500
C	1525F-35	VIK							12,000
C	1525G-45	VIK							12,000

MATERIALS PROPERTIES
LITERATURE

TABLE 2: MATERIALS PROPERTIES - MECHANICAL (Con't.)

RIGID MATERIALS TARGET PROPERTIES			THERMAL SHOCK RESISTANCE	SHRINKAGE V = VOLUME L - LINBAR	AGE SHRINKAGE	HARDNESS A-D = SHORE	IMPACT RESISTANCE	ELONGATION	SERVICE TEMPERATURE -55°C to +105°C	HEAT DISTORTION TEMPERATURE	COEFFICIENT OF THERMAL EXPANSION	THERMAL CONDUCTIVITY
EPOXIES												
UNFILLED												
SCOTCHCAST	5	3M	Fail			35 Barcol		1.4%			$177x10^{-10}/°C$	$4.4x10^{-4}$ Cal-cm
SCOTCHCAST	8	3M	Pass MIL-I-16923			70 D		50%			$15x10^{-5}/°C$	$4.2x10^{-4}$ Cal-cm
ISOCHEMREZ	460	ISO		.85%L		88 D			-55°C + 250°C	192°C	$6.2x10^{-5}/°C$	$4.8x10^{-4}$ Cal-cm
SCOTCHCAST	280	3M	Pass MIL-I-16923			65 D		85%			$21x10^{-5}/°C$	$5.3x10^{-4}$ Cal-cm
STYCAST	1264	EC	10 -45°F+160°	5.0% V	.51%	84-D	50 in-lb		185°F		$5.9x10^{-5}/°F$	
ISOCHEMREZ	402-LV	ISO		.88%L		86-D			-35°C to+190°C	118°C	$6.2x10^{-5}/°C$	$4.5x10^{-4}$ Cal-cm
CONAPOXY	1M-1145	CON		2.1% L		80-D		7%				
NORDBAK	1-0012	REX	Pass Washer -55°C +155°C			61-D						
NORDBAK	1-0021	REX	Pass Washer -55°C +155°C			40 D		75%				
FILLED												
SCOTCHCAST	281	3M	Pass MIL-I-16923			65 D		45%			$15x10^{-5}/°C$	$12x10^{-4}$ Cal-cm
PR	2200	FRI		5 Mil/inch²		75-D			-55°C+170°C	95°C	$2.7x10^{-5}/°C$	3.4 BTU-in
PDR	1322	DOL				72-D						
ISOCHEMPEZ	402AF	ISO		.49%L		88-D			-35°C+150°C	132°C	$5.3x10^{-5}/°C$	7.8 BTU-in
ISOCHEMPEZ	405M50	ISO		.48L		88 D			-45°C+200°C	165°C	$5.1x10^{-9}/°C$	8.2 BTU-in
SCOTCHCAST	9	3M	Pass MIL-I-16923			70-D					$13x10^{-5}/°C$	$7.4x10^{-4}$ Cal-cm
STYCAST	1090	EC		3.1% V	0%	76-D			-65°F+280°F		$2.06x10^{-5}/°F$	.86 BTU-in
STYCAST	10951	EC		2.8% V	0%	76-D			225°F		$2.2x10^{-5}/°F$	.7 BTU-in
STYCAST	2651 MMER	EC	Pass 10 MIL-I-16923	2.8% V	0%	92-D	.2 ft lb/in 1200		-65°F+350°F		$1.9x10^{-5}/°F$	1.02 BTU-in
STYCAST	2850 FT	EC		1.7% V	0%	84-D	.3 ft lb/in 1200		300°F		$1x10^{-5}/°F$	3.3 BTU-in
HYSOL	C-68	HY	Pass-55°C	.1% L		120 Rock-M	.45 ft-lb/in 1200			100°C	$23.5x10^{-6}/°C$	3.34 BTU-in
SCOTCHCAST	XR-5068	3M						0%	265°F		$13x10^{-5}/°C$	$5.7x10^{-4}$ Cal-cm
SCOTCHCAST	247	3M	MIC-1-16923 TYP C	2.1% Vol	0%	57 Shore D	12 Ft-lb	54%	265°F			.37 BTU-in
RIPLEY RESIN	484-YD-10	RIP	Pass -55° to 150°C			87 D		9.2%				.37 BTU-in
RIPLEY RESIN	494-YD-10	RIP	Pass -55° to 150°C			88 D		9.2%				
RIPLEY RESIN	2468-MA-3	RIP	Pass -55°C to 150°C			87 D		6.3%			$2.8x10^{-5}/°F$	.57 BTU-in
NORDBAK	1-0059	REY	Washer -55°C-155°C			75 D						
NORDBAK	1-0061	REY	Washer -55°C-155°C			60 D					$20x10^{-5}/°C$	
HYSOL	ES0254	HY		8%				9%				
HYSOL	977-87			1.85%L				1.65%				$7.31x10^{-4}$ Cal-cm
POLYESTER												
UNFILLED												
STYPOL	40-1021	FRE				40 A2		250%				
STYPOL	40-1124	FRE		8.4%		70 A2						
STYPOL	40-1037	FRE										
FILLED												
STYPOL	40-1602	FRE		7.2%		70 D			-55°C + 105°C			
STYPOL	40-1603	FRE		6.7%		60 D			-55°C + 105°C			
URETHANES												
UNFILLED												
CONATHANE	EN-2526	COM		.93 L		80 D		10%	-20°C+130°C		$21x10^{-5}/°C$	$2.8 x 10^{-4}$ Cal-cm

MATERIALS PROPERTIES
LITERATURE

TABLE 2: MATERIALS PROPERTIES - MECHANICAL (Con't.)

RIGID MATERIALS			MODULUS TENSILE	MODULUS FLEXURAL	MODULUS COMPRESSIVE	STRENGTH TENSILE	STRENGTH FLEXURAL	STRENGTH COMPRESSIVE	VISCOSITY
TARGET PROPERTIES			500,000 psi	450,000 psi	425,000 psi	700 psi	psi	psi	cps
EPOXIES									
UNFILLED									
SCOTCHCAST	5	3M				6200	19,000	23,800	3000
SCOTCHCAST	R	3M				2000	1,400	3,000	5500
ISOCHEMREZ	460	ISO				9200		16,000	26,000
SCOTCHCAST	280	3M				1950	425	2,400	4000
STYCAST	1264	EC							440
ISOCHEMREZ	402-LV	ISO				4800		6,800	550
CONAPOXY	IM-1145	CON				7000			1400
NORDBAK	1-0012	REX				2400		30,000	650
NORDBAK	1-0021	REX				500		510	1500
FILLED									
SCOTCHCAST	281	3M				2100	1,250	3,500	48,000
PR	2200	FRI				10,500		16,000	5,000
PDR	1322	DOL							2,500
ISOCHEMREZ	402AP	ISO				6200		8,500	2,800
ISOCHEMREZ	405M50	ISO				9000		16,000	17,500
SCOTCHCAST	9	3M				2500	2,600	4,500	
STYCAST	1090	EC			238,000		4,200	16,000	20,000
STYCAST	10951	EC			250,000		4,000	10,000	18,000
STYCAST	2651 MMER	EC				7000	12,000	17,000	4,500
STYCAST	2850 FT	EC		2×10^6	1.1×10^6	8400	13,300	16,500	70,000
HYSOL	C-68	HY					12,500	30,500	17,000
SCOTCHCAST	XR-5068	3M						110 psi	Powder
SCOTCHCAST	247	3M				1250	265	1,390	35,000
RIPLEY RISIN	484-YD-10	RIP				4400			28,500
RIPLEY RESIN	494-YD-10	RIP				4400			30,000
RIPLEY RESIN	2468-MA-3	RIP				4400			56,000
NORDBAK	1-0059	REY				3400		11,800	7,000
NORDBAK	1-0061	REY							2,000
HYSOL	ES0254	HY		3×10^5		4000	7,000		10,000
HYSOL	977-87			9.55×10^5		9636	13,644		
POLYESTER									
UNFILLED									
STYPOL	40-1021	FRE				400			280
STYPOL	40-1124	FRE							175
STYPOL	40-1037	FRE							250
FILLED									
STYPOL	40-1602	FRE				1800	620		35,000
STYPOL	40-1603	FRE							35,000
URETHANES									
UNFILLED									
CONATHANE	EN-2526	COM				5600			280

MATERIALS PROPERTIES
LITERATURE