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Plasma Current Collection of Z-93 Thermal Control Paint as Measured in the Lewis Research Center's Plasma Interaction Facility

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PLASMA CURRENT COLLECTION OF Z-93 THERMAL CONTROL PAINT AS MEASURED IN THE LEWIS RESEARCH CENTER'S PLASMA INTERACTION FACILITY

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SUMMARY

A sample of Z-93 thermal control paint was exposed to a simulated space environment in a plasma chamber. The sample was biased through a series of voltages ranging from -100 volts to +300 volts and electron and ion currents measured. Currents were found to be in the microampere range indicating that the material remains a reasonably good insulator under plasma conditions. As a second step, the sample was left in the chamber for six days and retested. Collected currents were reduced by from two to five times from the previous values indicating a substantial loss of conductivity. As a final test, the sample was removed, exposed to room conditions for two days, and returned to the chamber. Current measurements showed that the sample had partially recovered the lost conductivity. In addition to presenting these results, this report documents all of the experimental data as well as the statistical analyses performed.

INTRODUCTION

Z-93, a paint composed of zinc oxide in a potassium silicate binder, has been widely used in the space program as a thermal control coating. Recently, there has been an increased interest in the electrical properties of this paint because of its anticipated use on surfaces which may be at high electrical potentials with respect to the ionospheric plasma.

In particular, the radiators baselined for Space Station Freedom will be coated with Z-93. The measurement of plasma current collection from such surfaces is important because the ground potential of large space structures with respect to the ionosphere can differ significantly from that of the plasma. This occurs as a result of current balance. Because of their large mass and low mobility, ions collected by negatively biased surfaces result in a relatively small plasma current density. The lightweight electrons, on the other hand, are readily collected by positively biased surfaces. Ram and wake effects further complicate the picture. Ram ion energy is considerably higher than ambient thermal energy so ion collection is enhanced on ram facing surfaces relative to surfaces which are oblique to plasma flow. The spacecraft will reach equilibrium at whatever potential results in a net collection current of zero. The most challenging situations occur when the spacecraft power system uses a negative ground as does, for example, Space Station Freedom. In such a configuration, large surfaces are negative and must collect slow moving ions to balance the current from electron collection which now occurs only from relatively small areas of positive surface. In the worst case, parts of the spacecraft will be biased negatively with respect to the ionosphere to a level very near the maximum voltage used on the solar arrays.

An initial assessment of the implications for Space Station Freedom (SSF) was made by a workshop which included most of the recognized experts in NASA, industry, and academia[1]. That assessment showed that plasma effects are expected to have considerable impact on the performance and surface properties of SSF. As a result, a NASA "Tiger Team" was formed to comprehensively evaluate all related issues and to recommend any necessary action[2]. This team, consisting of more than 100 people including most of the experts mentioned above, worked for more than a year to study these issues. Extensive computer modeling and ground based plasma testing was performed and incorporated into an exhaustive set of trade studies.

The Tiger Team concluded that major parts of SSF would "float" at about 140 V negative with respect to the ionosphere, close to the 160 V maximum used by its power system. Such large potentials would be expected to involve major difficulties with arcing and sputtering and clearly cannot be tolerated. To address this problem a plasma contactor is being added to SSF. Basically a hollow cathode discharge, the contactor will emit a continuous cloud of plasma which will effectively "ground" the structure to the ionosphere. The result will be that as conditions change throughout the orbit, the floating potentials on various parts of the structure will oscillate between positive and negative. The design parameters for the contactor will be chosen to keep the amplitudes of these potentials to within ± 40 volts of plasma ground. In order to properly design the contactor, it is necessary to model the overall system of "station plus contactor plus ionosphere". This in turn requires an understanding of the plasma current collection characteristics of the various surfaces. Because of the large area of the radiators, which comprise about half the surface area of the entire space station, a moderately conducting coating would be expected to considerably affect current balance. In particular, if the Z-93 coated radiators are a good conductor of plasma electrons the plasma contactor will have to be larger to compensate for the resulting current during the positive part of the cycle.

A standard measurement of the material conductivity is inadequate for this determination for two reasons. First, plasma is not a standard electrode for bulk conductivity measurements and a measurement made with metal electrodes cannot be expected to produce the same result. Second, since there is no way of knowing how much of the applied bias "drops" over the thickness of the material, one can not easily calculate the plasma current conduction from a knowledge of the bulk conductivity. A direct measurement of the plasma current characteristics of Z-93 was therefore undertaken and is reported here.

TEST FACILITY AND PROCEDURES

Testing was done in the Plasma Interaction Facility (PIF) at the Lewis Research Center. The plasma chamber used was a Tenney Corporation space simulation chamber offering a cylindrical volume six feet in diameter by six feet long. A thirty six inch diffusion pump provides an initial pumpdown to approximately 5×10^{-7} torr. Plasma is generated by a tungsten filament source with a continuous flow of Argon. Pressure in the tank during operation of the plasma source was approximately 5×10^{-5} torr.

An electrometer, a Keithley model 237, was used to apply a bias voltage to the test sample and measures the resulting collected current. The measurements were made from -100 volts to +300 volts in 10 volt increments. Ion and electron current sweeps were made separately, always beginning with zero volts and increasing the applied voltage. The negative bias range was restricted to -100 volts to avoid arcing and possible damage to the sample. A complete data set consisted of five runs which were averaged to smooth random fluctuations. Additional precautions were necessary to account for systematic drifts in plasma density caused by conditions in the plasma source. Filament sources generally degrade as the tungsten evaporates and the resistance slowly increases. The result is a slow increase in filament temperature and a resulting increase in measured plasma density. To account for this, the plasma density was monitored using a 3/4 inch Langmuir probe. At the beginning of each data run, the plasma source was adjusted to result in a current of 800 microamps when this probe was biased to +100 volts. It was observed that this current would typically increase by two or three percent by the time the run was completed. Plasma conditions corresponding to this value were measured and are shown in Table I. The procedure effectively normalizes all data to the plasma density indicated. Figure 1 shows a schematic representation of the experimental layout.

Table I - Plasma Parameters

Electron Density	3.3×10^5 / cm^3
Electron Temp	1.20 eV
Ion Temp	.123 eV
Plasma Potential	2.95 eV

The electrometer used to measure the sample was controlled by a laboratory PC while the one used for the monitor probe was operated from its front panel controls.

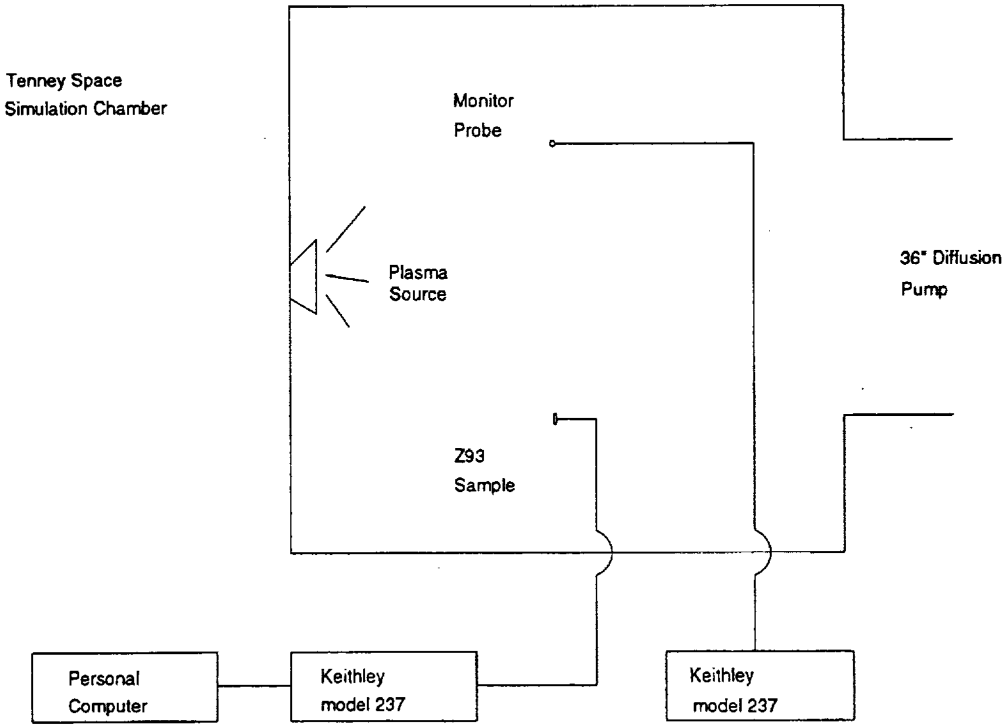

Figure 1 - Block diagram of the Test Facility and layout

The sample was provided by the Electro-Physics branch at the Lewis Research Center. It is a disk nominally 15/16 inch in diameter[3] and 1/32 inch thick. Z-93 is applied to one face of the disk with a coating thickness of between four and five mils. Electrical connection is made to the back face and all exposed metal surfaces sealed with Kapton tape and a clear silicon sealant.

The Z-93 test was performed in three parts. First, the sample was placed in the tank and a set of measurements taken. It was then allowed to remain in the tank for six days. During this time, other work was proceeding intermittently so that the sample saw a plasma environment during much of each day and vacuum conditions the remaining time. At the end of the six day period, the test was repeated. As will be discussed below, the measured currents decreased as a result of the extended exposure to tank conditions. The sample was then removed from the tank and simply hung in a corner of the laboratory for approximately sixty hours. It was then returned to the tank and the measurements repeated a third time.

RESULTS

A summary of the data, giving the mean and standard error, is shown in table II. All raw data is tabulated in the appendix. To help understand the meaning of the results, a direct comparison of Z-93 with a metal sample was also made. The sample was made of copper and was constructed to be as close as possible in size, exposed surface, and use of insulating materials on the back and on cable connections. Data from the metal sample is presented along with the Z-93 data.

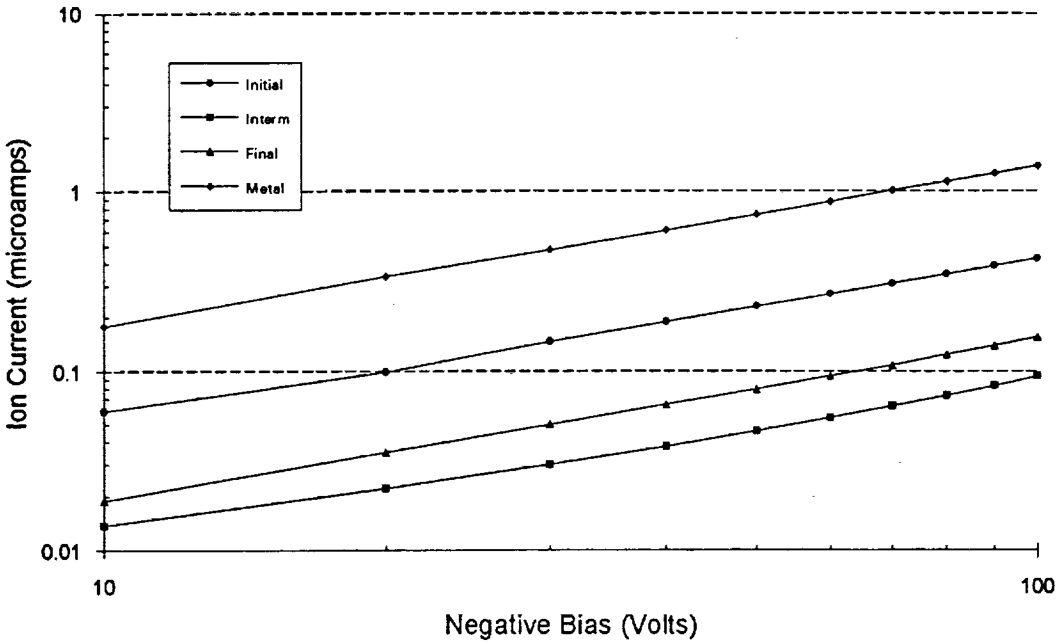

Figure 2 - Ion Current Vs Applied Bias

Table II - Data Summary

Ion Current

Volts	Initial		Intermediate		Final		Metal	
	Mean µA	Standard Error	Mean µA	Standard Error	Mean µA	Standard Error	Mean µA	Standard Error
-100	-0.427	0.0033	-0.094	0.0041	-0.155	0.0002	-1.374	0.0480
-90	-0.388	0.0030	-0.083	0.0030	-0.139	0.0000	-1.252	0.0468
-80	-0.349	0.0028	-0.073	0.0029	-0.124	0.0002	-1.130	0.0443
-70	-0.310	0.0026	-0.064	0.0022	-0.108	0.0002	-1.006	0.0422
-60	-0.270	0.0024	-0.055	0.0016	-0.095	0.0002	-0.878	0.0400
-50	-0.230	0.0022	-0.046	0.0012	-0.080	0.0002	-0.746	0.0367
-40	-0.189	0.0020	-0.038	0.0008	-0.065	0.0002	-0.611	0.0320
-30	-0.146	0.0017	-0.030	0.0006	-0.050	0.0003	-0.476	0.0261
-20	-0.099	0.0012	-0.022	0.0003	-0.035	0.0003	-0.340	0.0195
-10	-0.060	0.0007	-0.014	0.0002	-0.019	0.0003	-0.179	0.0118

Electron Current

Volts	Mean µA	Standard Error	Mean µA	Standard Error	Mean µA	Standard Error	Mean µA	Standard Error
10	0.103	0.0026	0.036	0.0003	0.061	0.000	5.192	0.7164
20	0.194	0.0047	0.058	0.0005	0.115	0.000	14.600	1.5063
30	0.286	0.0067	0.082	0.0008	0.184	0.001	27.800	2.4333
40	0.371	0.0083	0.101	0.0011	0.262	0.002	44.480	3.3460
50	0.444	0.0093	0.130	0.0014	0.349	0.002	65.260	4.3025
60	0.515	0.0105	0.162	0.0020	0.451	0.003	92.780	5.3796
70	0.592	0.0119	0.199	0.0025	0.569	0.003	127.000	5.6036
80	0.680	0.0134	0.252	0.0032	0.713	0.003	164.000	5.7706
90	0.784	0.0148	0.314	0.0049	0.930	0.005	202.400	5.2688
100	0.912	0.0165	0.400	0.0068	1.166	0.007	238.200	4.4430
110	1.037	0.0187	0.508	0.0085	1.638	0.004	270.800	3.3675
120	1.262	0.0136	0.648	0.0132	2.148	0.006	301.200	2.6344
130	1.561	0.0168	0.914	0.0202	2.682	0.006	329.800	2.2672
140	1.968	0.0067	1.168	0.0242	3.210	0.010	357.400	1.9131
150	2.454	0.0097	1.492	0.0307	3.938	0.014	384.200	1.7720
160	3.036	0.0227	1.848	0.0322	4.638	0.009	410.400	1.6310
170	3.698	0.0310	2.274	0.0401	5.442	0.007	436.400	1.6310
180	4.508	0.0186	2.774	0.0520	6.246	0.009	462.000	1.7029
190	5.459	0.0312	3.362	0.0573	7.164	0.014	487.400	1.9131
200	6.479	0.0225	4.094	0.0950	8.170	0.021	513.400	1.9131
210	8.268	0.1485	5.456	0.2495	9.482	0.054	538.800	1.8547
220	9.775	0.0221	6.732	0.1454	10.880	0.020	564.600	1.9131
230	11.264	0.0233	8.014	0.1589	12.340	0.051	592.000	1.7607
240	12.953	0.0425	9.498	0.2280	13.760	0.068	621.000	0.9487
250	14.965	0.0762	11.140	0.2205	15.420	0.102	650.200	0.5831
260	17.583	0.1863	13.020	0.3247	17.280	0.086	676.400	0.8718
270	20.682	0.3587	15.700	0.3493	21.020	1.527	702.600	1.0296
280	24.216	0.1892	19.400	0.6870	31.980	1.514	738.200	5.4166
290	27.462	0.1201	22.860	0.7979	43.460	5.282	837.800	24.4651
300	32.518	0.2177	28.460	0.8778	56.940	6.433	905.200	7.8447

The ion current data is plotted in figure 2. Error bars are not presented since the standard errors are generally in the range of 1 or 2 percent of mean value and would present a cluttered appearance. As can be seen, current collection is linear with bias voltage in all cases. Comparison of the initial Z-93 curve with the metal sample shows that the effective conductivity is a factor of three smaller. The intermediate curve is reduced from the initial one by an almost constant factor of 5 and only partially recovers after 2 days of room air exposure.

The electron current data is plotted in figure 3. The initial data shows a linear dependence on bias up to 100 volts followed by a sharp break in the curve. Effective conductivity is about fifty times smaller than the metal sample. For higher voltages, the current collection increases approximately with the third power of applied voltage. This is may be due to some sort of snapover effect or to a change in the actual material properties of Z-93. Since the metal sample appears to undergo a change at the same point in the curve, it is likely that this is a plasma sheath effect characteristic of this geometry and insulating materials. In any event, the overall experimental sample appears to become significantly more conducting at this voltage, an effect that was observed in all five runs comprising this data set.

The intermediate data set shows a reduction in conductivity, after six days in the chamber, similar to what was observed in the ion collection data. Below 100 volts this reduction is about a factor of three and is much less so at higher voltages. The data shows a break at about 100 volts, as before, but it is not so abrupt.

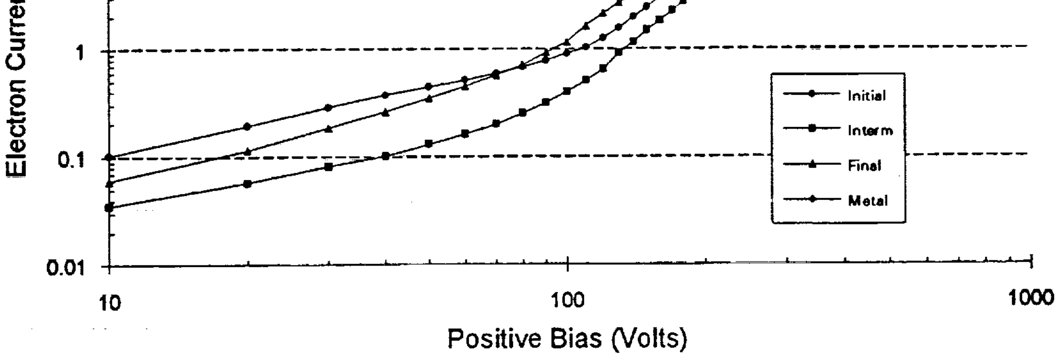

Figure 3 - Electron Current Vs Applied Bias

The final curve, representing two days of room exposure, indicates a partial recovery up to about 80 volts. After this point, the effective conductivity increases rapidly and apparently exceeds even the initial value. The final curve and, to a lesser extent the intermediate one, show a pronounced "hump" in the 120 volt to 160 volt range. The reasons for this behavior are not clear but may involve some sort of breakdown or change in the material properties at high voltages. Within the limited range of interest for the plasma contactor, ± 40 volts, the results are consistent for both ion and electron collection.

CONCLUSIONS

The ability of Z-93 thermal control paint to conduct current from a simulated space plasma was measured directly in a space simulation chamber. For ions the effective conductivity was found to be reduced by about a factor of three from that of metal. For electrons, currents were observed to be a factor of fifty smaller than metal. The actual effect on Space Station Freedom cannot be determined without sophisticated modeling, which will procede as part of the plasma contactor program, but from these results it would seem unlikely that surfaces coated with Z-93 will make any significant contribution to plasma contactor currents.

REFERENCES

1. Ferguson, D.C., Snyder, D.B., and Carruth, R., Final Report of the Joint Workshop on Evaluation of Impacts of Space Station Freedom Grounding Configurations, NASA LeRC, Aug, 1990.

2. Brewer, D., "Minutes of the Space Station Freedom Electrical Grounding Tiger Team", Space Station Freedom Project Office, Reston VA, unpublished.

3. J. Dever, Personal Communication, NASA Lewis Research Center, Cleveland, OH, 1992

APPENDIX - RAW DATA

Initial - July 23, 1992

Ion Current

Volts	Run1 μA	Run2 μA	Run3 μA	Run4 μA	Run5 μA
-100	-0.422	-0.433	-0.434	-0.429	-0.417
-90	-0.384	-0.393	-0.394	-0.389	-0.378
-80	-0.346	-0.354	-0.355	-0.350	-0.340
-70	-0.308	-0.315	-0.315	-0.310	-0.301
-60	-0.270	-0.275	-0.275	-0.270	-0.262
-50	-0.231	-0.235	-0.234	-0.230	-0.222
-40	-0.191	-0.193	-0.192	-0.188	-0.182
-30	-0.148	-0.149	-0.148	-0.145	-0.140
-20	-0.100	-0.102	-0.101	-0.099	-0.095
-10	-0.057	-0.061	-0.061	-0.060	-0.059

Electron Current

Volts	Run1 μA	Run2 μA	Run3 μA	Run4 μA	Run5 μA
10	0.111	0.106	0.103	0.099	0.096
20	0.208	0.199	0.193	0.186	0.181
30	0.307	0.294	0.286	0.276	0.269
40	0.396	0.381	0.371	0.359	0.349
50	0.472	0.456	0.445	0.430	0.419
60	0.547	0.528	0.516	0.499	0.487
70	0.627	0.606	0.593	0.574	0.559
80	0.720	0.696	0.680	0.660	0.643
90	0.830	0.802	0.783	0.762	0.746
100	0.963	0.932	0.910	0.886	0.869
110	1.096	1.058	1.035	1.010	0.989
120	1.304	1.278	1.262	1.243	1.225
130	1.582	1.588	1.594	1.529	1.512
140	1.964	1.955	1.957	1.975	1.991
150	2.448	2.419	2.466	2.465	2.473
160	2.978	2.988	3.049	3.079	3.088
170	3.630	3.672	3.653	3.735	3.801
180	4.458	4.469	4.542	4.545	4.526
190	5.366	5.482	5.410	5.497	5.540
200	6.395	6.516	6.489	6.519	6.475
210	7.694	8.470	8.499	8.402	8.277
220	9.822	9.799	9.809	9.735	9.710
230	11.295	11.173	11.281	11.300	11.270
240	12.942	12.905	13.012	13.075	12.829
250	15.027	15.020	15.131	14.968	14.679
260	18.150	17.792	17.592	17.290	17.090
270	21.750	21.217	20.511	20.184	19.750
280	24.784	24.394	24.090	24.183	23.629
290	27.719	27.312	27.288	27.784	27.205
300	32.923	31.985	32.962	32.714	32.004

Intermediate - July 29, 1992

Ion Current

Volts	Run1 μA	Run2 μA	Run3 μA	Run4 μA	Run5 μA
-100	-0.110	-0.090	-0.089	-0.090	-0.091
-90	-0.095	-0.080	-0.079	-0.080	-0.081
-80	-0.085	-0.070	-0.070	-0.071	-0.071
-70	-0.072	-0.061	-0.061	-0.062	-0.062
-60	-0.061	-0.053	-0.053	-0.053	-0.054
-50	-0.051	-0.045	-0.045	-0.045	-0.045
-40	-0.041	-0.037	-0.037	-0.037	-0.037
-30	-0.032	-0.029	-0.029	-0.030	-0.030
-20	-0.024	-0.022	-0.022	-0.022	-0.022
-10	-0.015	-0.014	-0.014	-0.014	-0.014

Electron Current

Volts	Run1 μA	Run2 μA	Run3 μA	Run4 μA	Run5 μA
10	0.035	0.035	0.036	0.037	0.036
20	0.057	0.058	0.058	0.060	0.058
30	0.080	0.081	0.082	0.085	0.082
40	0.098	0.100	0.102	0.105	0.101
50	0.126	0.129	0.130	0.135	0.130
60	0.157	0.160	0.162	0.169	0.162
70	0.193	0.197	0.199	0.208	0.198
80	0.245	0.249	0.251	0.264	0.251
90	0.302	0.311	0.312	0.332	0.312
100	0.390	0.388	0.397	0.426	0.397
110	0.494	0.499	0.500	0.541	0.505
120	0.628	0.634	0.640	0.700	0.637
130	0.907	0.910	0.886	0.991	0.877
140	1.160	1.160	1.140	1.260	1.120
150	1.490	1.490	1.470	1.600	1.410
160	1.840	1.830	1.820	1.970	1.780
170	2.270	2.270	2.230	2.420	2.180
180	2.780	2.770	2.710	2.960	2.650
190	3.380	3.340	3.280	3.570	3.240
200	4.150	4.050	3.950	4.430	3.890
210	5.730	5.630	5.240	6.070	4.610
220	6.870	6.690	6.560	7.200	6.340
230	8.130	7.980	7.830	8.540	7.590
240	9.560	9.450	9.260	10.300	8.920
250	11.300	11.000	10.900	11.900	10.600
260	13.300	12.900	12.600	14.100	12.200
270	15.800	15.600	15.700	16.800	14.600
280	20.400	19.400	18.800	21.200	17.200
290	23.700	22.600	22.200	25.300	20.500
300	28.800	29.300	28.300	30.600	25.300

Ion Current

Volts	Run1 μA	Run2 μA	Run3 μA	Run4 μA	Run5 μA
-100	-0.154	-0.155	-0.155	-0.155	-0.154
-90	-0.139	-0.139	-0.139	-0.139	-0.139
-80	-0.123	-0.124	-0.124	-0.124	-0.123
-70	-0.108	-0.108	-0.108	-0.108	-0.107
-60	-0.095	-0.095	-0.095	-0.095	-0.094
-50	-0.080	-0.080	-0.080	-0.080	-0.079
-40	-0.065	-0.065	-0.065	-0.065	-0.064
-30	-0.050	-0.050	-0.051	-0.050	-0.049
-20	-0.035	-0.035	-0.036	-0.035	-0.034
-10	-0.019	-0.019	-0.020	-0.019	-0.018

Electron Current

Volts	Run1 μA	Run2 μA	Run3 μA	Run4 μA	Run5 μA
10	0.0606	0.0611	0.0612	0.0608	0.0609
20	0.114	0.115	0.115	0.115	0.116
30	0.181	0.183	0.184	0.185	0.187
40	0.256	0.259	0.261	0.264	0.268
50	0.343	0.346	0.349	0.352	0.357
60	0.443	0.446	0.45	0.454	0.46
70	0.561	0.564	0.568	0.573	0.579
80	0.705	0.708	0.712	0.715	0.725
90	0.922	0.915	0.93	0.936	0.945
100	1.16	1.16	1.17	1.15	1.19
110	1.63	1.63	1.64	1.64	1.65
120	2.16	2.13	2.14	2.15	2.16
130	2.67	2.67	2.68	2.69	2.7
140	3.24	3.19	3.19	3.2	3.23
150	3.89	3.93	3.94	3.96	3.97
160	4.63	4.62	4.63	4.64	4.67
170	5.43	5.43	5.44	5.44	5.47
180	6.23	6.24	6.24	6.24	6.28
190	7.2	7.16	7.13	7.14	7.19
200	8.18	8.14	8.14	8.14	8.25
210	9.65	9.31	9.47	9.47	9.51
220	10.9	10.8	10.9	10.9	10.9
230	12.5	12.4	12.3	12.2	12.3
240	14	13.8	13.7	13.6	13.7
250	15.8	15.4	15.4	15.2	15.3
260	17.6	17.3	17.2	17.1	17.2
270	27.1	19.7	19.9	19.1	19.3
280	35.5	30.3	30.4	28.1	35.6
290	46.7	34.3	41.3	32.9	62.1
300	77.4	45.4	44.8	50.7	66.4

Metal - August 13, 1992

Ion Current

Volts	Run1 μA	Run2 μA	Run3 μA	Run4 μA	Run5 μA
-100	-1.22	-1.32	-1.39	-1.45	-1.49
-90	-1.10	-1.20	-1.27	-1.33	-1.36
-80	-0.99	-1.08	-1.14	-1.20	-1.24
-70	-0.871	-0.959	-1.02	-1.07	-1.11
-60	-0.751	-0.832	-0.89	-0.943	-0.975
-50	-0.63	-0.703	-0.756	-0.806	-0.835
-40	-0.51	-0.574	-0.619	-0.664	-0.689
-30	-0.394	-0.445	-0.482	-0.518	-0.54
-20	-0.278	-0.317	-0.345	-0.372	-0.387
-10	-0.142	-0.164	-0.181	-0.198	-0.208

Electron Current

Volts	Run1 μA	Run2 μA	Run3 μA	Run4 μA	Run5 μA
10	3.17	4.17	5.18	6.24	7.2
20	10.3	12.5	14.6	16.8	18.8
30	20.8	24.4	27.9	31.4	34.5
40	34.8	39.9	44.6	49.4	53.7
50	52.7	59.4	65.6	71.6	77
60	76.8	85.5	93.6	101	107
70	110	120	128	135	142
80	146	157	166	172	179
90	186	196	204	210	216
100	224	233	240	245	249
110	260	267	272	276	279
120	293	298	302	305	308
130	323	327	330	333	336
140	352	355	357	360	363
150	379	382	384	387	389
160	406	408	410	413	415
170	432	434	436	439	441
180	457	460	462	464	467
190	482	485	487	490	493
200	508	511	513	516	519
210	534	536	538	542	544
220	559	562	565	567	570
230	589	588	592	593	598
240	619	619	621	622	624
250	649	649	650	651	652
260	674	675	677	677	679
270	700	701	703	703	706
280	728	747	729	755	732
290	867	774	826	807	915
300	918	899	925	880	904

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13. ABSTRACT ***(Maximum 200 words)***

A sample of Z-93 thermal control paint was exposed to a simulated space environment in a plasma chamber. The sample was biased through a series of voltages ranging from −100 volts to +300 volts and electron and ion currents measured. Currents were found to be in the microampere range indicating that the material remains a reasonably good insulator under plasma conditions. As a second step, the sample was left in the chamber for six days and retested. Collected currents were reduced by from two to five times from the previous values indicating a substantial loss of conductivity. As a final test, the sample was removed, exposed to room conditions for two days, and returned to the chamber. Current measurements showed that the sample had partially recovered the lost conductivity. In addition to presenting these results, this report documents all of the experimental data as well as the statistical analyses performed.

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