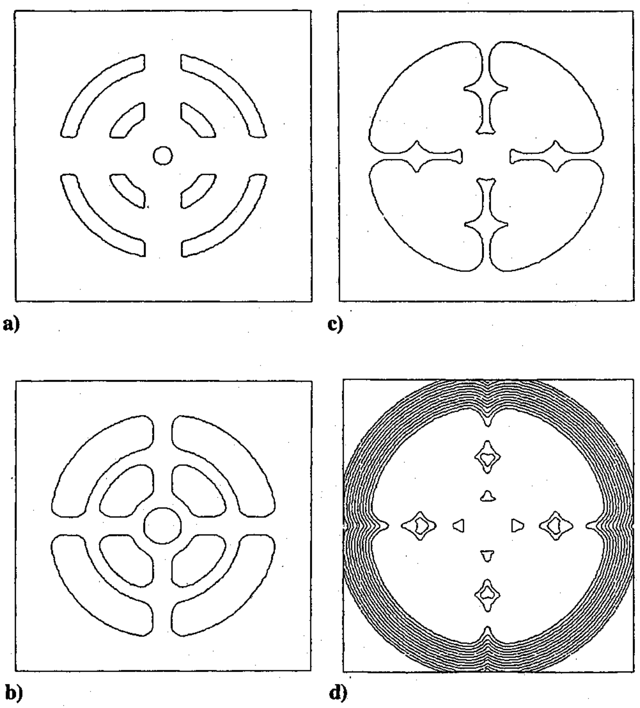

Fig. 5 Shape evolution of a multiperforated grain.

and then the new burning velocity is determined for use in the next time step.

We have implemented this technique to find the shape evolution of a grain configuration shown in Fig. 5a. The f field defined by this configuration is given as the initial condition to the FLAIR algorithm. The port area of the grain is calculated by adding the initial port area to the summation of all the f values at any time and subtracting it from the initial total of f values. The perimeter is obtained by adding the length of interface lines in the cells located on the boundary. And the burning area of the propellant, A_b, is determined by multiplying the perimeter by the length of the grain. In each case we have started with 100×100 square cells. Since only the advection in the internal surface of the grain is concerned here, a square section for the outer geometry of the grain is used. However, any other geometries can be simply designed with this technique. The time increment is not constant and changes with the variation in burning velocity. The merging of surfaces is easily handled with FLAIR technique, and very complicated propellant grain shapes such as the one shown in Fig. 5c are resolved. Figure 5d shows the existence of some propellant residue in the inner zone of the chamber, which may result in the roughness in the pressure curves.

Concluding Remarks

A new technique for solid-propellant grain design has been developed by using a model for advection and interface reconstruction entitled FLAIR. This technique imposes no limitation on grain configuration, and it is capable of handling any variation of burning velocity with time and position along the burning surface. This technique can be an excellent alternative to the presently used geometrical techniques for solid-propellant grain design. Another advantage of this technique is that the performance of a solid-propellant grain that has some defects, such as cracks and cavities, can be obtained as long as the initial shape of the grain cross section with its defects is described.

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Measured Plasma Conductivity of Zinc-Oxide-Based Thermal Control Coatings

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Introduction

Z93, a coating 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 increased interest[1,2] in the electrical properties of this coating because of its anticipated use on surfaces that may be at high electrical potentials with respect to the ionospheric plasma.

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. The spacecraft will reach equilibrium at whatever potential results in a net collection current of zero.

The radiators baselined for International Space Station Alpha (ISSA), for example, will be coated with Z93. In the case of ISSA it was shown[1,2] that major parts of the structure 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. To force the structure closer to plasma potential an active control device, a plasma contactor, is being added to ISSA. Basically a hollow-cathode discharge, the contactor will emit a continuous cloud of plasma that will effectively "ground" the structure to the ionosphere. Current understanding of plasma interactions and their effect on the floating potential has been incorporated into sophisticated computer codes, which will be used to design ISSA as well as future space power systems. These in turn require an understanding of the plasma-current collection characteristics of the various surfaces. Because of the large area of the radiators, which constitute about half the surface area of the entire space station, a moderately conducting coating would be expected to affect the current balance considerably. An accurate value for the conductivity is therefore essential for modeling and simulation.

Within the past year, the binder used in the formulation of Z93 has become unavailable and will no longer be made by the current supplier. This binder is a potassium silicate material made by Sylvania and designated as PS7. An effort has therefore been underway to qualify a replacement. After extensive effort, a reformulated product, using a potassium silicate material made by Philadelphia Quartz corporation and known as Kasil 2130, has been approved and designated Z93P. Although the two formulations are intended to be as close to identical as possible, the qualification process has concentrated on such issues as sprayability, adhesion to substrates, and long-term stability in low earth orbit. Electrical conductivity in a plasma has not been specifically addressed. The two formulations differ slightly in such parameters as the density, the amounts of metallic impurities, and the mole fractions of various constituents.[3]

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It is beyond the scope of this work to relate any difference in conductivity to a single material parameter or combination of them. It is simply noted that the materials are not identical and that measurements will be made on both.

A standard measurement of the material conductivity is inadequate for this determination, since in a plasma part of the applied bias "drops" over the material and part over a plasma sheath. A direct measurement of the plasma current characteristics of Z93 and Z93P was therefore undertaken and is reported here.

Test Facility and Procedures

Two samples of Z93 and two of Z93P were measured. The samples are aluminum disks nominally 1 in. in diameter and 1/32 in. thick. The coating is applied to one face of the disk with a nominal thickness of between 4 and 5 mils. Electrical connection is made to the back face, and all exposed metal surfaces are sealed with a clear silicon sealant. All measurements were made in a space simulation chamber offering a cylindrical volume 6 ft in diameter by 6 ft long. A 36-in. 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. The 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 measure the resulting collected current. The measurements were made from −200 to +200 V in 10-V increments. Ion and electron current sweeps were made separately, always beginning with 0 V and increasing the applied voltage. Precautions were taken to minimize the effect of 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-in. Langmuir probe. At the beginning of each data run, the plasma source was adjusted to result in a current of 800 μA when this probe was biased to +100 V. It was observed that this current would typically increase by 2–3% by the time the run was completed. Plasma conditions corresponding to this value were measured and are shown in Table 1. 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.

In making a measurement of the conductivity of an insulating coating on a metal surface, it seems intuitively clear that all of the applied voltage will drop over the coating, i.e., that the metal will not account for any significant bias drop. In a plasma, however, a sheath will form over a biased conducting surface and will support a voltage drop. An issue to be resolved is whether the sheath drop is a significant fraction of the total voltage, which can be true if the coating is even weakly conducting. To determine the conductivity unambiguously we therefore made measurements of the current collection from an identical sample of pure copper. By comparing the voltages at which the two samples collect an identical current, the magnitude of the sheath effect can be determined.

In practice, the metal sample was mounted in the tank to one side of center, and the coating sample placed symmetrically on the other side. Five data runs were then taken from both coating and metal. The tank was then opened, the positions of the coating sample and metal sample reversed, and five more runs taken. The monitor probe, whose position never changed, was relied on to reproduce overall plasma conditions. This procedure accounted for small differences in plasma conditions from one side of the tank to the other caused by the nonsymmetric placement of the plasma source. All 10 runs were then averaged to produce the final data.

Preliminary work[4] with Z93 showed that the material required about 1 week in vacuum to reach a stable conductivity. Further, an exposure of several days to room humidity only partially restored conductivity. All samples were therefore left in the chamber under high vacuum for 2 weeks before beginning the tests reported here. When the tank was opened to reposition a sample, the process required a maximum of 10 min of exposure to humidity. These changes were always performed in the afternoon, and no data taken until the next day. Samples not under test remained in the chamber at all times. This procedure is believed sufficient to minimize any effects of humidity and to insure that all samples had an identical history of exposure.

Table 1 Plasma parameters

Electron density	$4.5 \times 10^5/\mathrm{cm}^3$
Electron temperature	1.13 eV
Ion temperature	0.25 eV
Plasma potential	3.05 eV

Results

Although the same metal sample was used to produce all four data sets and despite our best efforts to provide identical plasma conditions from run to run over the several weeks that the data were taken, current collection from the metal sample shows differences of as much as a factor of 2. One of the metal sample sets was chosen for normalization, i.e., for the four coating samples the averaged currents will be multiplied by the ratio of the current collected by the corresponding metal sample to that collected by the normalization sample at each value of applied bias. As expected for a conductor, current collection from the metal sample was linear with applied bias in all cases.

Collection from our samples was well behaved over most of the voltage range. Attempts to extend the voltage range to 300 V, however, resulted in sharp increases in current collection. We take this as evidence of breakdown in either the silicon coating used to cover exposed metal parts or in the coating material itself. One Z93-P sample had such problems in the 150–200 V range.

To estimate the importance of sheath effects, it is noted that the maximum ion current measured, neglecting the breakdown experienced by sample Z93P-1, was approximately 25 μA. By comparison, such a current is collected by the metal sample with the application of between 2 and 3 V, implying that all of the applied bias "drops" over the paint layer except for 2 or 3 V, which is supported by the sheath. In principle, one could fit these curves and interpolate to obtain an accurate value. This number would then be a correction to be applied to the voltage for the coating sample effectively shifting the X axis in the current-vs-voltage curves. Since the relative magnitude is small, we simply accept an error of several volts in our voltage scale and note that for the work reported here it is not significant. A more detailed description of this analysis is available elsewhere.[5] For electron collection, the case is even more clear cut. The coating sample collects less than 1 μA of current while the metal sample is collecting milliamperes. Any correction here is truly insignificant.

To convert current collection results to conductivity, one simply calculates the conductance by dividing current by voltage and dividing the result by the area of the sample, 5.07×10^{-4} m^2. For convenience, the results are presented in units of 10^{-6} S/m^2 in Figs. 1 and 2. Examination of the figures shows that the conductivity of Z93P is approximately 0.5 μS/m^2 for both electrons and ions. In Fig. 1, we assume that the curve for sample Z93P-1, which closely paralleled that of the second sample up to about 130 V, would have continued to do so had no breakdown occurred. Over the range of particular interest, 50 to 150 V, the conductivity appears to be essentially con-

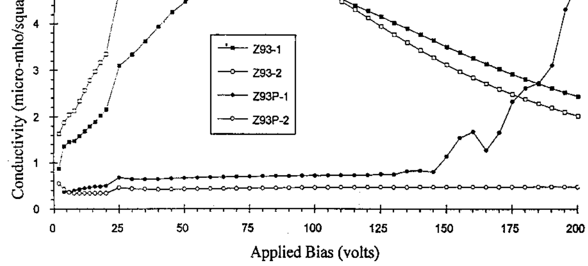

Fig. 1 Ion conductivity vs applied bias.

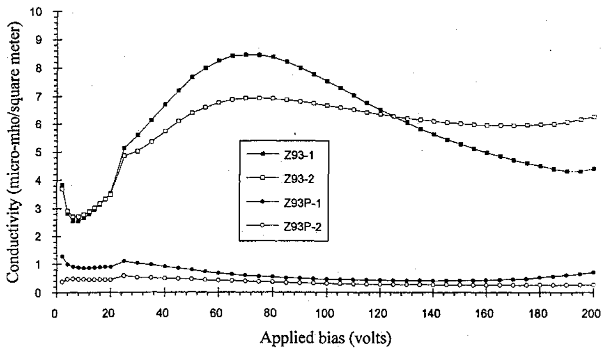

Fig. 2 Electron conductivity vs applied bias.

stant. Figure 2 supports the same conclusion for electron collection, i.e., a constant conductivity.

Conductivity for Z93 shows a more pronounced dependence on voltage for both electron and ion conductivity. While these curves may be used for more accurate estimates, one can say that the conductivity over the 50- to 150 V range is approximately a factor of 10 larger than for Z93P.

In estimating the overall error in our reported results, recall first that data were taken in five run sets. Data from metal samples shows typical standard errors in the 1 to 2% range, indicating stable, reproducible plasma conditions. Data from the coating samples, however, show much larger errors, generally 20 to 30% in magnitude. These relatively large errors are not, however, randomly distributed, but indicate a systematic effect in the experiment. Since the runs were not all taken at the same time, comparison of the time history of the runs with raw data indicates that the history of the sample in the 15 to 20 min previous to a run is critical. Specifically, if two runs are taken with no delay between them, the second differs from the first by as much as a factor of 2. If, however, 15 to 20 min is allowed to pass, the second run reproduces the first to within a few percent. Since the samples are exposed to active plasma at all times, we do not believe this to be a residual charging effect. Apparently, the application of high voltage to this material temporarily alters its bulk properties in a way that requires a significant time to relax. The mechanism is unknown and will be the subject of future research relating to this family of coatings. This effect, along with the 2- to 3-V error in our voltage scale discussed above, leads us to believe that our final mean conductivities are conservatively accurate to no better than a factor of two.

Conclusions

The plasma conductivity of Z93 and Z93P thermal control coatings was measured directly in a space simulation chamber. For Z93P, which is assumed to be the baseline formulation for all future applications, the conductivity was found to be a nearly constant 0.5 $\mu S/m^2$. For Z93, the previous formulation, conductivity was approximately an order of magnitude larger and showed a somewhat more pronounced dependence on voltage. As is noted above, there are small differences in the composition of the binder between the two coatings, which presumably account for the measured differences in conductivity. These results are being incorporated into modeling for ISSA. Preliminary results[6] indicate that the conductivity we report here is two orders of magnitude too small to affect the current balance and floating potential significantly. Our results will be used to advocate the development of coatings with mechanical, thermal, and optical properties similar to Z93P but with an electrical conductivity that can be tailored to the application

Acknowledgments

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Launch Strategy Using Ground-Based Mass Drivers

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I. Introduction

THERE is current interest in developing a ground-based mass driver for accelerating payloads to near-orbital velocities.[1–3] This idea would exclude the possibility of delivering personnel, but supplies that could withstand high acceleration could be launched inexpensively several times a day. The idea presented here would make use of high-repetition drivers to accelerate small packages of matter. This would create a "fountain" to push a larger vehicle through the atmosphere and into space. The packages leaving the mass driver are envisioned as being slugs of solid material that can survive transit through the atmosphere yet disintegrate upon impact with a pusher plate at the aft of the accelerating vehicle. The repetition rate would be between 10 and 100 per second, and the relative velocity between the slugs and the vehicle would be held constant. The high repetition rate of the slug stream might make it easier for the following slugs to arrive at the vehicle. Note that this concept has been suggested before for powering interstellar missions,[4,5] where the benefits of a vacuum are present but extremely long distances are involved.

II. Momentum Transfer to Vehicle

Two components make up the propulsive effect when the slugs arrive at the vehicle. The first is the momentum transfer from collisions. This could take the form of each slug disintegrating upon impact with a flat plate, so that momentum is transferred in the amount of $m_s V_r$, where m_s is the mass of the slug and V_r is the relative velocity between the slug and the vehicle. Higher momentum transfer would result from a concave pusher plate. A second possible propulsive effect could arise from the kinetic or chemical energy that is delivered with the slugs. Only the case of momentum transfer will be considered here, and we further simplify the analysis by ignoring two effects, namely drag forces and Earth's gravity field. Both would be important in a detailed analysis, but the purpose of this write-up is to arrive at order-of-magnitude values for the major parameters describing the launch concept.

The required slug mass, relative velocity, and repetition rate can be worked out given the mission specifications. The baseline vehicle will have a mass of 10,000 kg and accelerate at a rate between 19.6 and 69.6 m/s^2 ($3g$ and $7g$). The final velocity will be arbitrarily set

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