D/0

N79-24011

THE CAPABILITIES OF THE NASA CHARGING ANALYZER PROGRAM*

I. Katz, J. J. Cassidy, M. J. Mandell,
G. W. Schnuelle, P. G. Steen
Systems, Science and Software

J. C. Roche
NASA Lewis Research Center

ABSTRACT

Desirable features in a spacecraft modeling code are enumerated. The NASCAP (NASA Charging Analyzer Program) is discussed in terms of its approach to the problem. Samples of problem set-up and output are provided which demonstrate the ease with which the program can be used. A simple but interesting case of spacecraft charging is examined and other applications are discussed.

INTRODUCTION

The basic concerns of a computer spacecraft model can be broken down into five areas.

1. Features of the spacecraft itself
2. Features of the environment
3. The spacecraft-environment interaction
4. Man-hours to set up and computer time to run a calculation
5. A way to verify the model

In modeling the spacecraft itself, the point is to get in as much detail as can reasonably be included. This will vary depending on the type of model being used. The features desired (Whipple (ref. 1)) are first, some geometrical detail, such as the basic shape of the spacecraft body and any protrusions such as booms and antennae. Second, one would want to include which parts of the surface are bare conductor and which are dielectric coated. Third, it would be nice to have some representation of the electrical circuitry connecting parts of the spacecraft surface.

---

*This work supported by the National Aeronautics and Space Administration, Lewis Research Center, under Contract NAS3-21050.

It is also important to decide what approximations go into the environment surrounding the spacecraft. The most basic decision is how to model the ambient plasma. Can you include the region far from the spacecraft, and get a detailed look at the region close in? Can you specify normal and extreme conditions? Does the plasma charge in time? Other aspects of the environment that are of concern are the sun, the plasma sheath, and particle trajectories.

The spacecraft-environment interaction is mainly a matter of particle currents to and from the spacecraft surface. The important charging currents are

1. Incident electrons
2. Photocurrent
3. Incident protons
4. Secondary electrons from electron impact
5. Secondary electrons from proton impact
6. Electron backscatter

These processes vary around the spacecraft surface, depending on local potential, surface material, and solar illumination. An ideal model would take all this local information into consideration when calculating particle fluxes.

Computer time for spacecraft modeling can be prohibitive. A model that is general ends up solving a series of equations with hundreds or thousands of variables. An exact solution is enormously expensive, and it may be hard to get convergence from an iterative solution. Much care must be put into this aspect of the problem, lest an otherwise elegant modeling program start to impersonate an infinite loop.

The most expensive way to verify a modeling program is to build a spacecraft like the model and send it up. Other, more reasonable techniques, are to model ground experiments, to check answers for reasonableness, and to test the program on known problems.

NASCAP APPROACH

As we have seen, the physics which must be examined in order to model spacecraft charging presents a problem of formidable dimensions. It would be impractical to develop a computer code that was state of the art in every aspect of the problem. By placing restrictions on the class of problems to be examined we have been able to construct the NASA Charging Analyzer Program which provides useful information in those cases of most practical interest. It is most applicable to the high voltage charging caused by magnetospheric substorms.

Our approach has been to limit the range of ambient environments to those whose Debye lengths, λ_D, are large compared to object dimensions. For magnetospheric substorms this is definitely true.

$\theta_e \sim 10{,}000$ eV

$n_e \sim 1\ cm^{-3}$

$\lambda_D \sim 0.7$ km

Only for the very largest conceivable spacecraft are object dimensions comparable to Debye lengths. For finite Debye lengths we have included ambient plasma screening approximations, albeit of modest applicability.

Overall, we have modeled all aspects of the problem except electromagnetic wave propagation. Our idea has been to use the best available analytical theories wherever possible and to minimize the brute force number crunching. By doing this we have been able to combine good treatments of ambient environment, sheath, complex object, and electrical and particle interactions into a single code. This is done by using known physics and developing approximate models where necessary. For example, NASCAP contains analytical approximations to electron backscatter as a function of electron energy and angle. While not as accurate as Monte Carlo transport results, these formulations do give reasonable yield estimates and can be evaluated quickly at hundreds of surface locations each timestep. Thus we obtain reasonable estimates in reasonable amounts of time as opposed to best estimates regardless of cost. This philosophy permeates the code. Where quasi-analytical models were necessary but unavailable, we have developed them.

The procedure followed in the code is to approximate the spacecraft in a 3-D Cartesian grid. Free space around the satellite is provided by nesting grids within grids where each grid has a linear dimension twice that of the grid it surrounds. There can be an arbitrary number of these nested grids. However, the more grids, the longer the computer time per calculation (fig. 1).

All parts of the spacecraft must remain in the innermost grid, except for booms which can extend into several grids. The object itself is composed of an assembly of cubes, sliced cubes, plane surfaces, and skinny cylinders, as shown in figure 2. Each surface can be of an independently specified material, with up to 15 different materials permitted (fig. 3). Certain classes of surfaces may be subdivided for higher resolution.

Object definition i[illegible] far the most complicated aspect of using a three-dimensiona[illegible] puter code. To make the program easy to use, NASCAP provi[illegible] an extremely simple object definition language. Complex three-dimensional spacecraft can be described with a minimum of effort. The satellite shown in figure 4 is a good example. The central structure is octagonal with a gold circumference and aluminum top and bottom surfaces. The two planar sheets represent solar cells with kapton covering the back surface. They are attached to the main body with kapton coated cylinders. This object was defined using 31 brief lines of input (fig. 5). The simple object definition commands are fully explained in the NASCAP User's Manual (ref. 2).

Once the object definition is complete, the program alternately calculates charge accumulations on surfaces and potentials caused by these charges. Due to the variety of timescales in the system, the algorithm used to advance the charge distribution in time is extremely complex, so complex that it uses a couple thousand element self-generated capacitor model as its own internal estimator.

NASCAP produces a variety of printed and graphical output. The fundamental idea is to help the user follow the progress of the calculation (figs. 6-14).

The first graphic output is a two-dimensional view of the spacecraft with surface cells shaded to show the material types. Each surface cell is individually classified by material, with up to 15 different material types allowed.

Next is a three-dimensional perspective view of the spacecraft without hidden line removal. This is helpful in tracking down object definition problems. It is followed by a view from the same perspective with surface cells outlined. In this surface cell plot, hidden lines are removed. The user gets a quick and accurate feeling for the defined object. The routine that generates these plots also calculates exposed surface areas for determining photoelectron emission.

These plots are generated at object definition time, before the actual satellite charging begins. The major outputs of the charging calculation are the flux breakdown printout and potential contours.

The flux breakdown printout shows, for any surface cell(s), the charging currents operating on that cell. Each individual surface cell requires a separate calculation. By requesting flux breakdown printouts, the user can closely follow the charging process at any point on the surface.

Contour plots are an efficient way to show what's happening to the electrostatic potential both near the spacecraft and far away. The user can look at the potential contour plots generated every time cycle and get a good feeling for global changes in the spacecraft sheath.

NASCAP detector routines plot flux density versus energy of particles reaching the detectors. Detectors can be placed, at the user's discretion, on any surface cell.

The emitter routines plot trajectories of particles emitted at various energies. These trajectories, along with potential contour plots, give a very good idea of fields surrounding the spacecraft or test tank object.

Finally, if local electric field stresses exceed some user specified threshold value, a message is printed and the code redistributes charge as if a discharge had occurred.

VALIDITY OF THE MODEL

With a model as broad in scope and as complex (over 400 subroutines) as NASCAP, the immediate question is "How do you know that it gets reasonable answers?" So that we have confidence in NASCAP results, testing and comparing to analytical results has been a major part of the development program. The accuracy of the various components have been examined in configurations simple enough to determine their inherent accuracy.

Since the capacitances of simple objects such as spheres, cubes and cylinders are known quite well, we have used these to determine how well the potential routines work. For all cases the NASCAP results were within 10 percent of analytical predictions, and for objects of more than a zone resolution and for booms of radius much less than the grid spacing, the NASCAP results were accurate to a few percent. The electric fields in space were of corresponding accuracy near the satellite and increasing accuracy away from the vehicle. The accuracy of the potentials are limited only by the ability of the finite element interpolation functions to represent the true solution. For complex objects, the NASCAP code uses the same algorithms and the accuracy should be comparable. Since NASCAP automatically takes into account mutual capacitances, it is a vast improvement over hand generated capacitor models for complex spacecraft.

NASCAP assumes that charge is accumulated on, as opposed to deposited within, dielectrics. Bulk conduction is included. We have performed detailed one-dimensional calculations of charge transport within dielectrics, and have found this to be a reasonable approximation for electrons of a few to tens of kilovolts in all but the thinnest of dielectrics. It is also an approximation that can easily be modified in the future if the need arises.

The charging currents are the algebraic sum of incident fluxes and backscattered, secondary, and photoemitted electrons. For spherical test cases we have compared NASCAP reverse trajectory currents with spherical probe formulas (ref. 3). Depending on the number of trajectories sampled the results were in reasonable agreement, the largest errors due to the differences between numerical and analytical integrals over angle of the backscatter and secondary emission formulas. Thus the two basic requirements of a charging calculation, the potential and charge accumulation, are performed well by NASCAP.

The NASCAP material interaction models have been developed from literature results. Their predictions are being compared with laboratory experiments and are the subject of another paper in this session. It should be pointed out, however, that NASCAP accepts parameters for these models as input and that the models themselves are contained in very short, easily replaceable subroutines. Consequently, modifications and improvements in the formulations can be made very simply if needed.

The particle trajectory algorithms are second order accurate in particle timesteps insuring good conservation of energy and magnetic moment. Orbits are followed beyond the outermost grid boundaries by using an extrapolation of the monopole potential. This allows long excursions of emitted particles to see if they return to the spacecraft.

The algorithm employed to integrate charging currents over a timestep is quite complex to ensure physical results. Rather than describe the technique in detail, we present a calculation which illustrates how it works.

A simple example, which nevertheless displays some of NASCAP's usefulness as a model, is the case of a spherical object in sunlight. Since the photocurrent is larger than the incident electron current, a capacitor-current balance model would lead one to the conclusion that a sunlit surface will remain at a positive potential relative to the surrounding plasma. However, the NASCAP charging current integration routines recognize that space charge limiting prevents photoelectrons and secondary electrons from supporting a potential barrier of more than a few volts. This feature, combined with the multidimensional aspects of the potential leads to a very different equilibrium, one with the illuminated surfaces a kilovolt negative.

We ran NASCAP for the case of a teflon coated sphere in sunlight. The environment for this case is an isotropic, Maxwellian plasma with a temperature of 20 keV and a density $n_e = n_i = 1\ cm^{-3}$. Sunlight was incident on one side of the sphere (fig. 15).

Figures 16-22 show the time development of the electrostatic field. (The satellite-sun line lies in the plane of these figures. Dark and sunlit cells are differentiated by shading.) For the first $\sim$0.1 second the sphere charged uniformly. Over the next few seconds, the negative charge accumulated by the shaded surfaces began to dominate the electrostatic field, causing a saddle point to appear in front of a sunlit surface. At about 10 seconds the potential at the saddle point became negative. The sunlit surface maintained a potential a few volts positive relative to the saddle point. Final steady state is reached with the sunlit surface at -1.0 kV and the shaded surface at -3.6 kV.

The final steady state potentials were reached at time t $\simeq$ 10^4 sec. This involved some 30 timesteps, and used total computer time of about one-half hour. Thus in a reasonable amount of computer time NASCAP can provide good physical insight into charging phenomena, insight which is unobtainable using simpler computer models.

4. APPLICATIONS OF NASCAP

NASCAP is designed primarily to give engineering estimates of spacecraft potentials during magnetospheric substorms. It also can provide detailed particle spectra for a given environment and spacecraft potential configuration in order to aid in interpreting results of scientific experiments. As of this time the applications of NASCAP have been limited to the comparison with laboratory material charging test results and to the generation of models of a few scientific spacecraft. Comparisons have been done to validate the material properties portion of the code. A later paper in this section (Roche, et al.) will discuss the results of these studies.

One application of NASCAP which is of engineering importance is the study of active charging control. The operation of onboard charged particle beams has been proposed as a means of minimizing the effects of ambient environment spacecraft charging. NASCAP features an emitter algorithm that models the trajectories and charge transfer effects of such beams. For example, we have placed a one kilovolt, one milliampere electron emitter on a satellite precharged to -2.5 kV. The potentials on spacecraft ground and on an insulated surface as a function of time are shown on figure 23. Notice that the insulator will differentially charge to a substantial negative potential. Sample particle trajectory plots during the charging phase are shown in figure 24. By modeling such systems NASCAP can estimate their utility and point out any severe design problems, so that actual flight experiments have the best chance for success.

An important problem, particularly in the future, is the interactions of large space structures. While not specifically designed for this application, the finite Debye length sheath treatment in the NASCAP code will combine with the reverse trajectory particle flux routines to give good estimates of space charge limited charge collection. The present algorithm employs linear

Debye shielding (figs. 25, 26). In the future, models of the ambient plasma sheath more relevant to dense collisionless plasmas, will be implemented. The object definition routines can already handle objects of large size by decreasing the object resolution (fig. 27).

The most ambitious application to date is the generation of the SCATHA model. This model utilizes the full capabilities of the code. The model and some preliminary calculations are the subject of the following paper.

REFERENCES

1. Whipple, E., "Proceedings of the Spacecraft Charging Technology Conference," 24 February 1977, p. 889.

2. Cassidy, J. J., "NASCAP User's Manual - 1978," NASA CR-159417, 1978.

3. Katz, I.; Parks, D. E.; Mandell, M. J.; Harvey, J. M. Brownell, Jr., D. H.; Wang, S. S. and Rotenberg, M., "A Three Dimensional Dynamic Study of Electrostatic Charging in Materials, NASA CR-135256, August 1977.

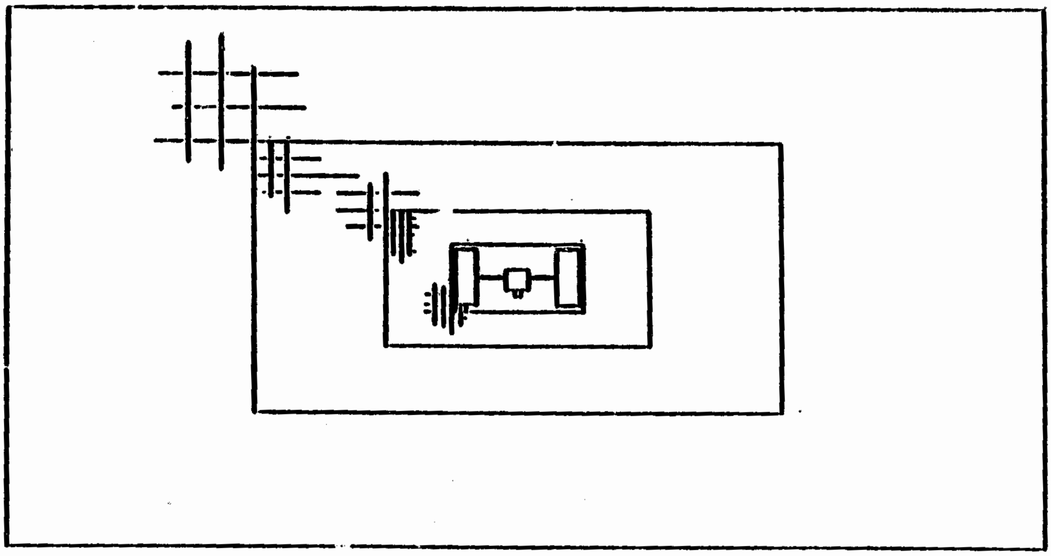

Figure 1. A two-dimensional view of the first four nested meshes. Each succeeding mesh increases the volume of calculation space by a factor of eight. Calculation time is roughly linear with the number of meshes.

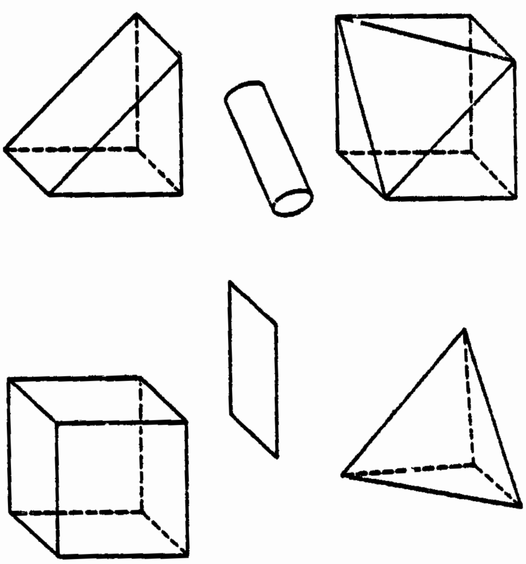

Figure 2. NASCAP can simulate virtually any object that can be built from these fundamental shapes - cube, three types of sliced cube, planar square, and thin cylinder.

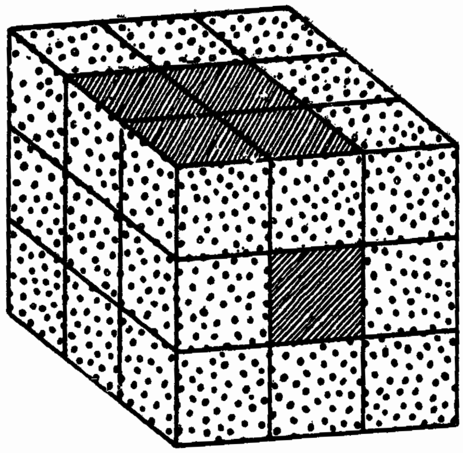

Figure 3. The spacecraft surface is made up of as many as 1200 surface cells. Each cell is assigned a material type and an underlying conductor. The surface cell may represent either bare conductor or dielectric layer.

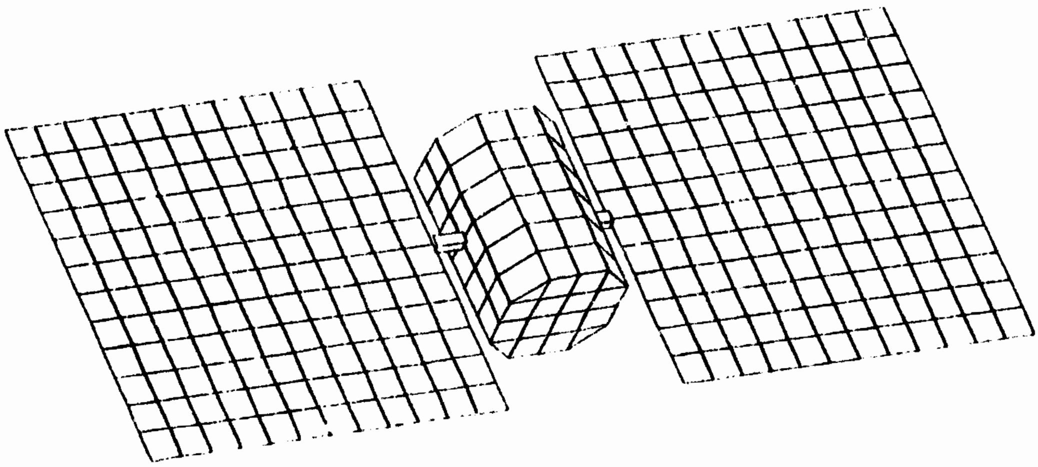

Figure 4. Paddle satellite. A geometrically complex object with four types of surface material.

```
[MATERIAL PROPERTIES DEFINITIONS]

OCTAGON
AXIS          -3     0    0          3    0    0
WIDTH          4
SIDE           2
SURFACE   -          ALUMINUM
SURFACE   C          GOLD
SURFACE   +          ALUMINUM
ENDOBJ
PLATE
CORNER        -6     0  -15
DELTAS        12     0   12
TOP       +Y        SIO2
BOTTOM    -Y        KAPTON
ENDOBJ
PLATE
CORNER        -6     0    3
DELTAS        12     0   12
TOP       +Y        SIO2
BOTTOM    -Y        KAPTON
ENDOBJ
BOOM
AXIS           0     0    2    1    0    0    3    1
RADIUS    0.2
SURFACE   KAPTON
ENDOBJ
BOOM
AXIS           0     0   -2    1    0    0   -3    1
RADIUS    0.2
SURFACE   KAPTON
ENDOBJ
ENDSAT
```

Figure 5. Object definition. The object in the preceding figure (paddle satellite) is defined by these commands.

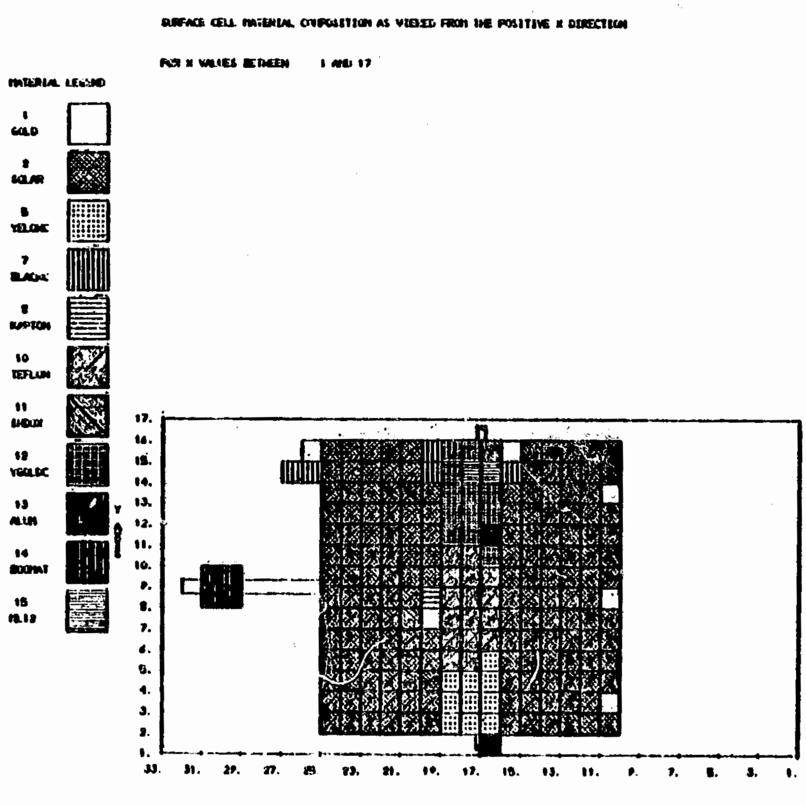

Figure 6. Satellite illustration plots show the material composition of each surface cell.

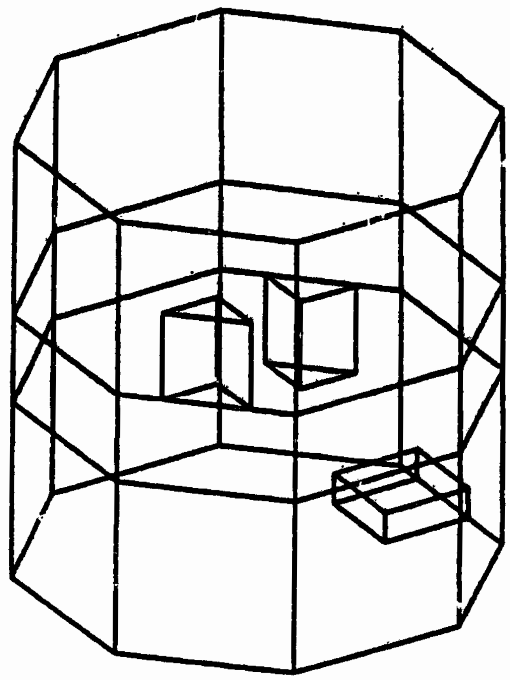

Figure 7. Object structural plots give a perspective view without hidden line removal.

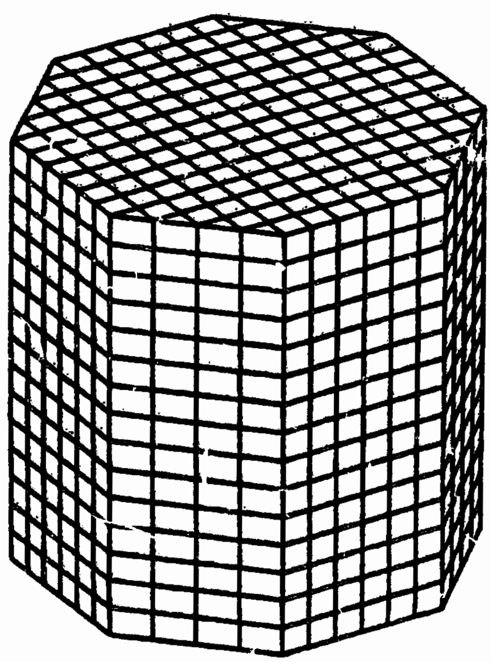

Figure 8. Surface cell hidden line plots give a clear idea of overall spacecraft structure.

```
SURFACE CELL NO.   15                                          CODE =        011112100702
                                                               LOCATION =     9 10  8
                                                               NORMAL =       0  1 -1
                                                               MATERIAL =    TEFLON
                                  POTENTIAL =  -1.096+01 VOLTS
                                  FIELD =    7.665-3 VOLTS/METER
FLUXES IN A/M**2
     INCIDENT ELECTRONS                                 3.16-06
          RESULTING BACKSCATTER                         8.60-07
          RESULTING SECONDARIES                         1.32-06
     INCIDENT PROTONS                                   7.39-08
          RESULTING SECONDARIES                         7.17-07
     PHOTOCURRENT                                       0.00
                                                      - - - - - -
   NET FLUX                                            -1.96-07
```

Figure 9. A breakdown of charging currents can be requested for any surface cell. This information is given at each timestep.

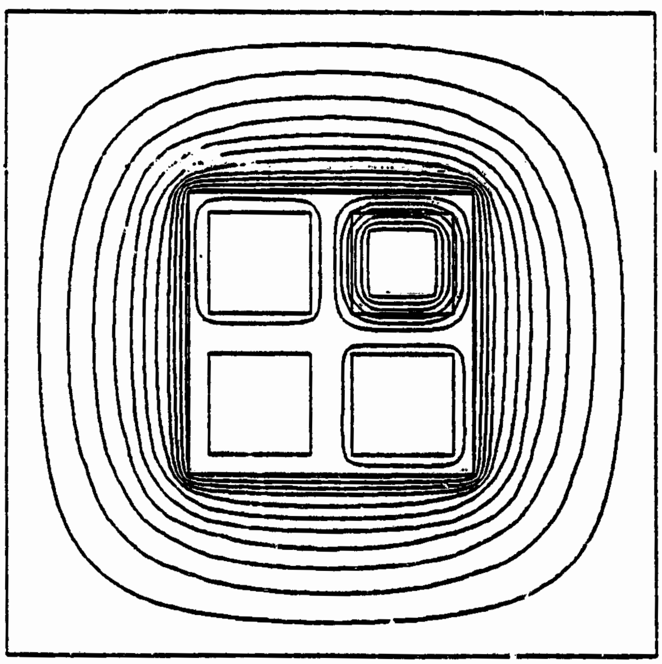

Figure 10. Two-dimensional potential contour plots give a clear picture of electrostatic potential at each timestep.

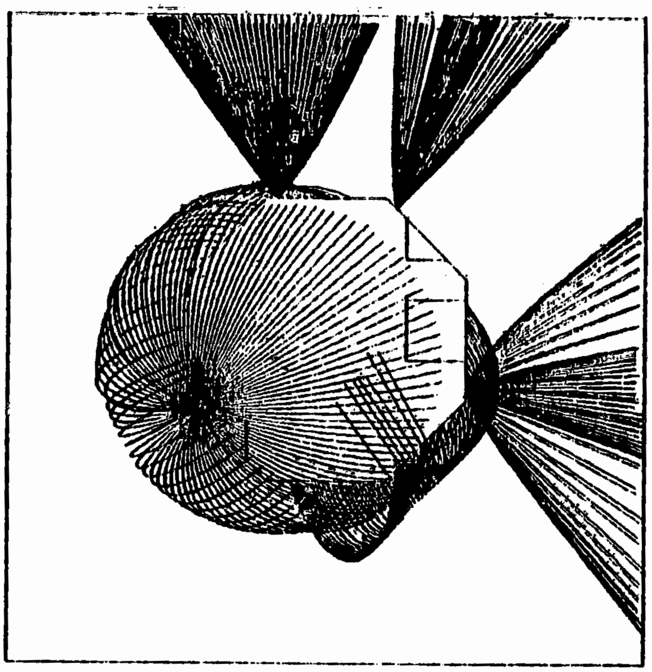

Figure 11. Particle emitters can be specified at any surface cell. This plot shows particles from five emitters for various angles of emission.

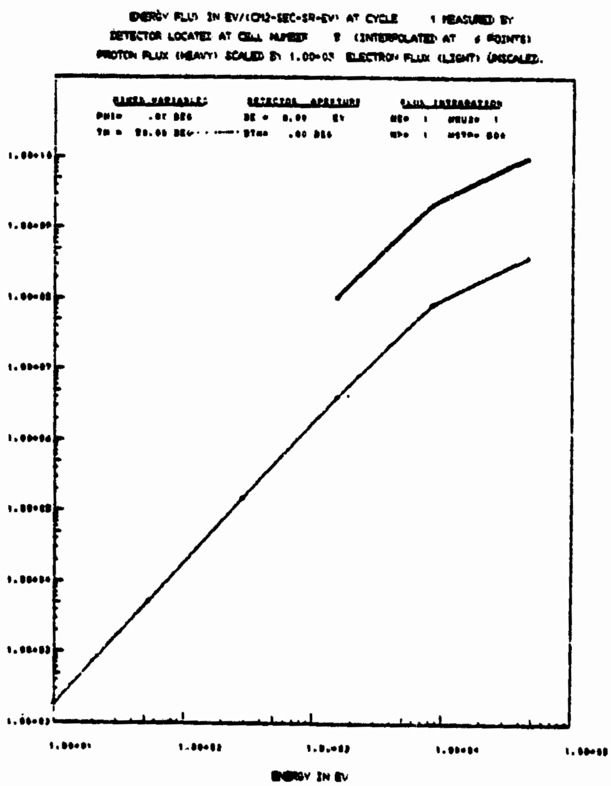

Figure 12. Particle detector plots show energy versus flux density. Detectors can also be located at any surface cell.

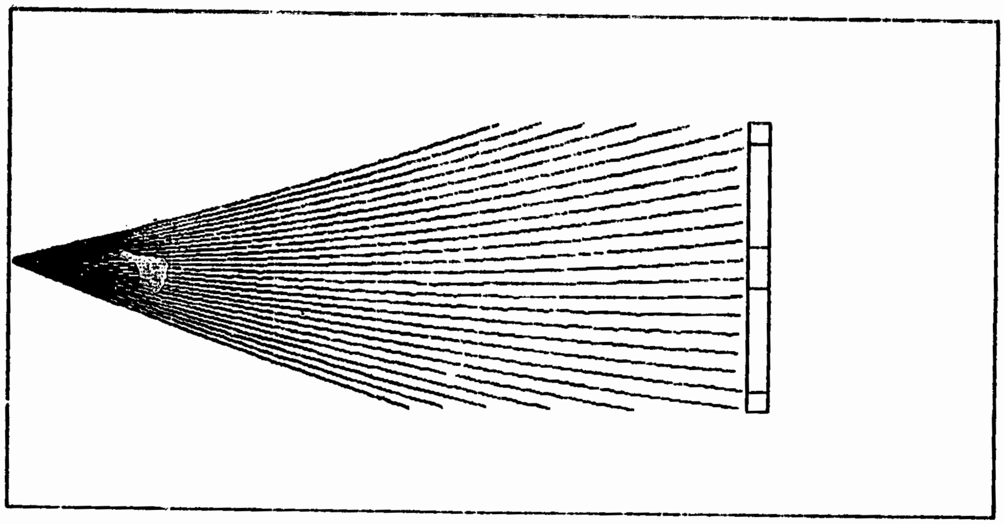

Figure 13. Graphic output for a test tank case includes trajectories of electrons from the source to the object.

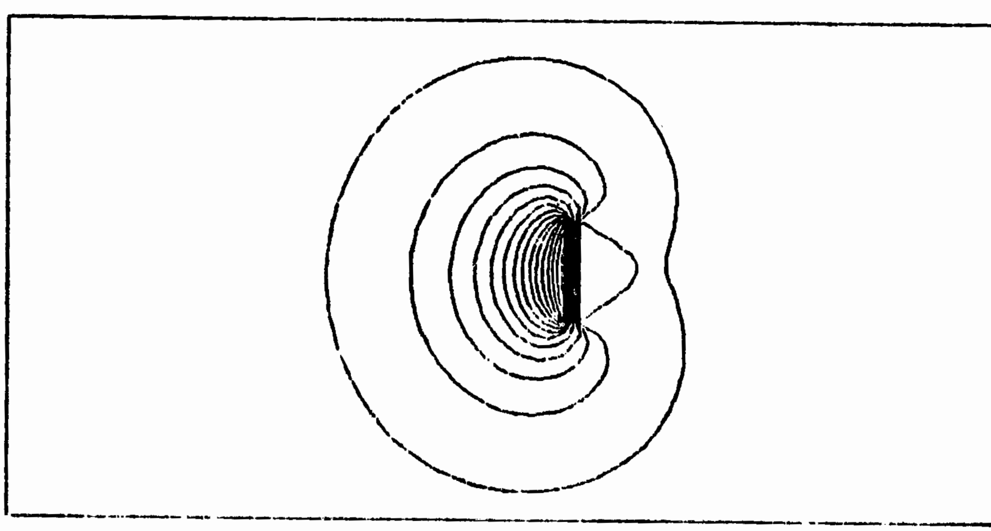

Figure 14. Potential contours around a fully charged teflon covered grounded plate in a ground test tank. An electron beam is coming from the left. Notice the fully formed potential saddle point to the right of the plate.

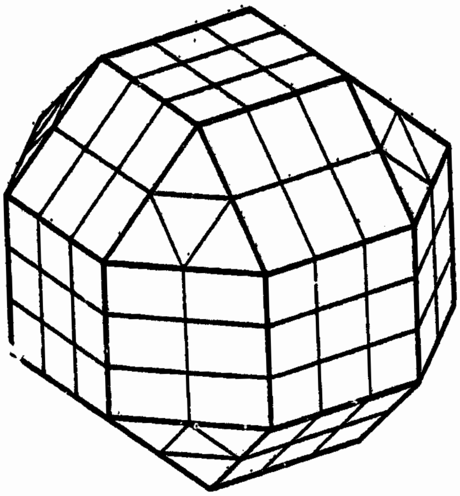

Figure 15. A NASCAP sphere – modeled as a twenty-six faceted object. This one is 3 meters in diameter with 158 surface cells and 144 surface nodes.

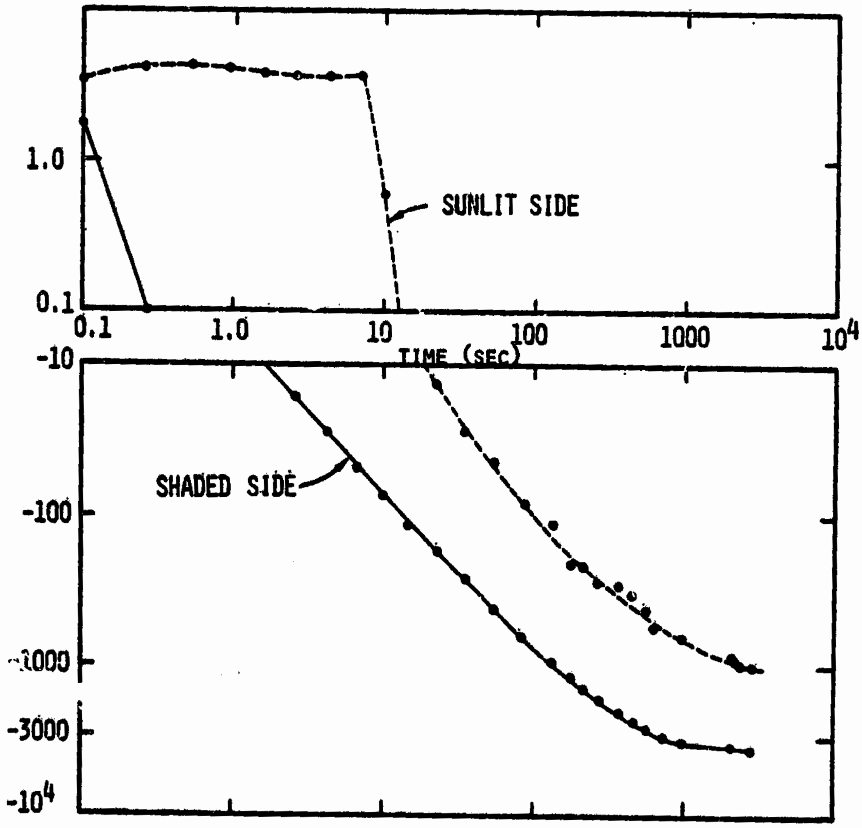

Figure 16. Potentials on shadowed and solar illuminated surfaces of a teflon sphere in a plasma ($N_e = 10^6/m^3$, $\theta = 20$ keV).

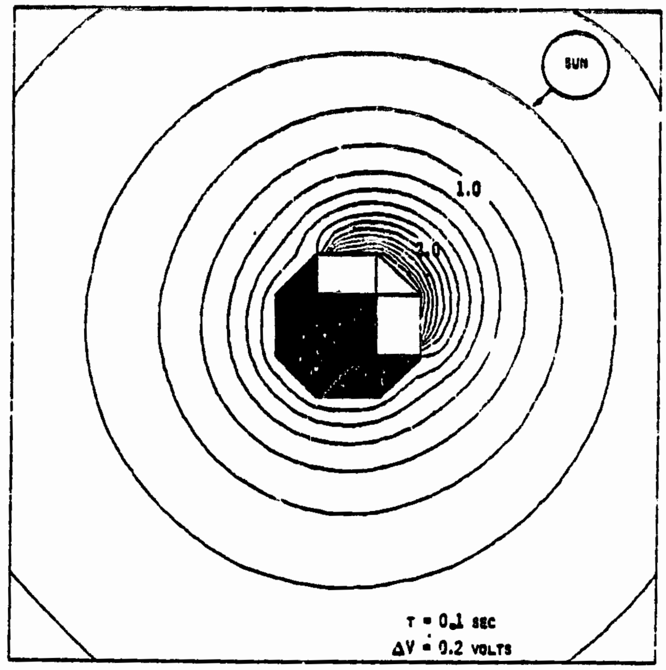

Figure 17. Potential contours about a sunlit sphere early in time.

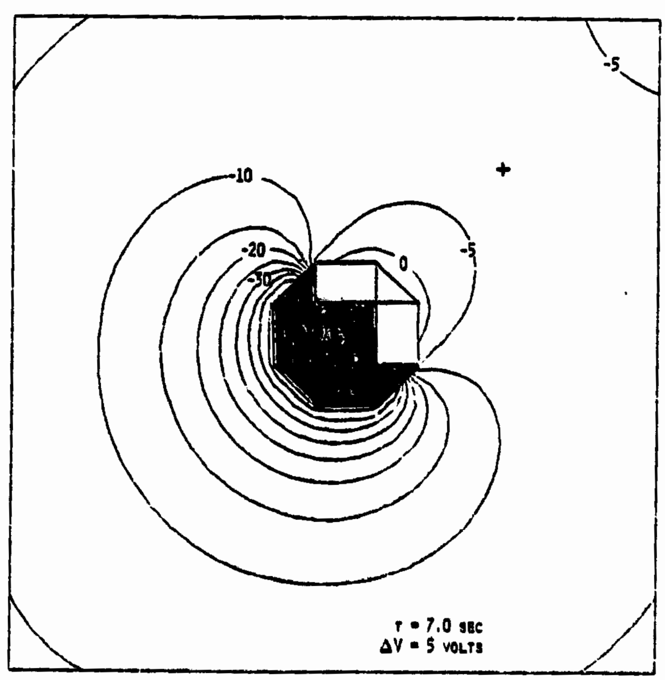

Figure 18. Potential contours around sunlit sphere showing early appearance of saddle point (+) at -5.6 volts.

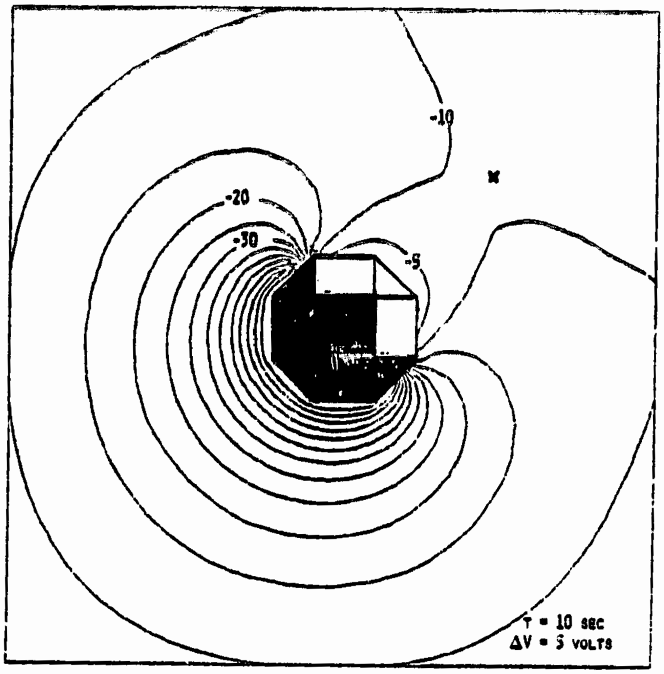

Figure 19. Potential contours around sunlit sphere showing fully formed saddle point at approximately -8 volts.

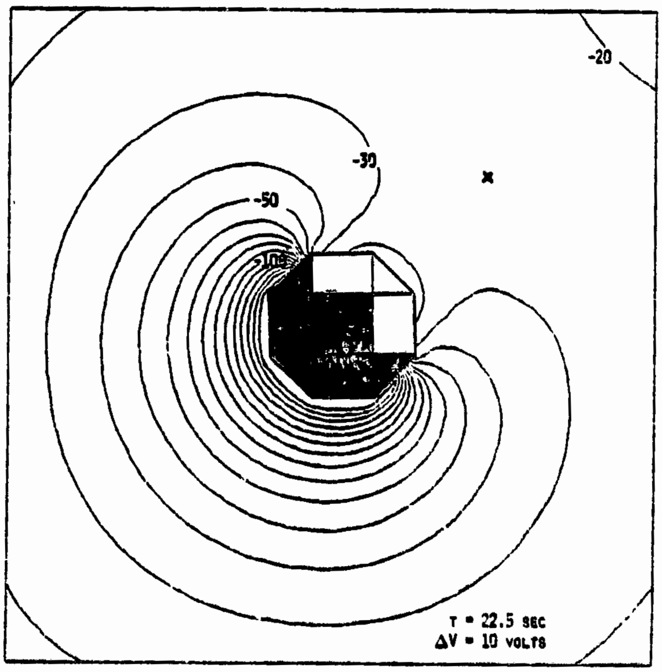

Figure 20. Potential contours about sunlit sphere showing saddle point at approximately -25 volts.

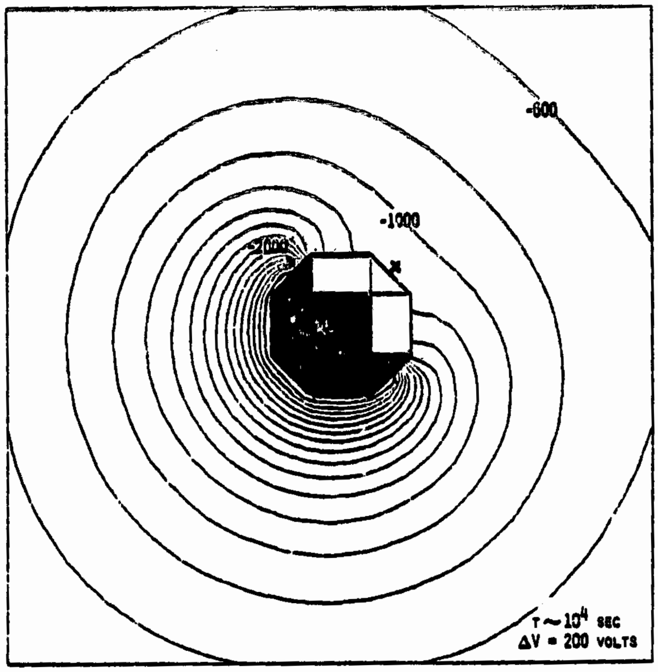

Figure 21. Steady state potential contours about sunlit sphere.

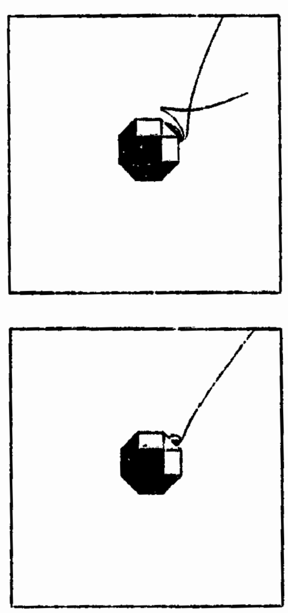

Figure 22. Trajectories of electrons emitted at various energies from fully charged sunlit sphere.

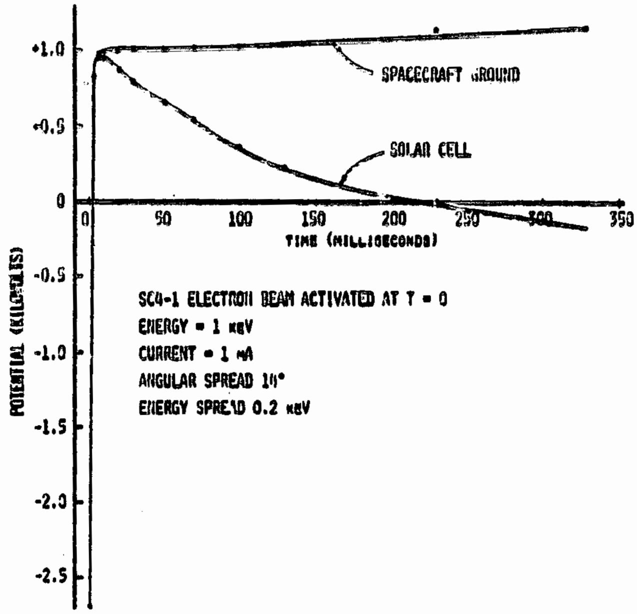

Figure 23. Active control simulation. A 1 mA particle emitter is activated with beam energy of 1 keV. The spacecraft goes from a negative 2.5 kV potential to positive 1.0 kV. Spacecraft ground remains at about that level while a solar cell on the surface falls back to a negative potential.

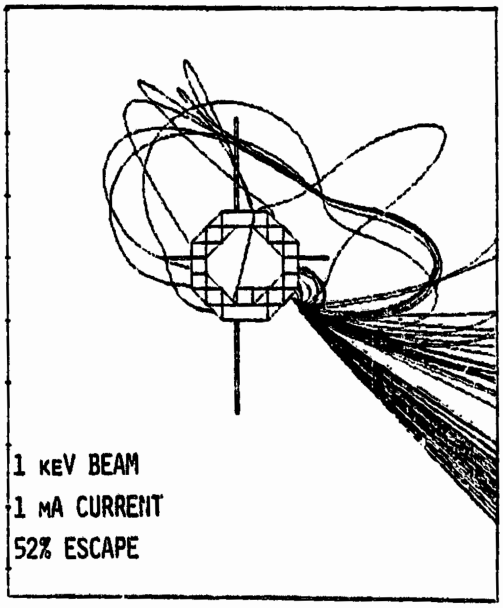

Figure 24. Particle emitter trajectory plot. Some of the emitted particles escape the spacecraft vicinity, while others return to various points on the surface.

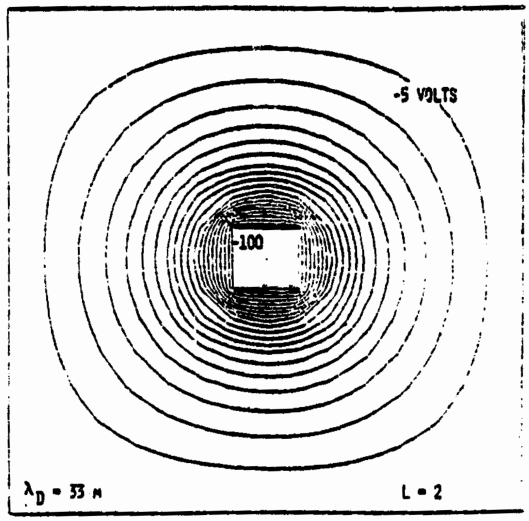

Figure 25. An approximate screening expression is employed to show shielding effects. Shown is a two meter cube charged to -100 V, in a plasma with Debye length of 33 meters.

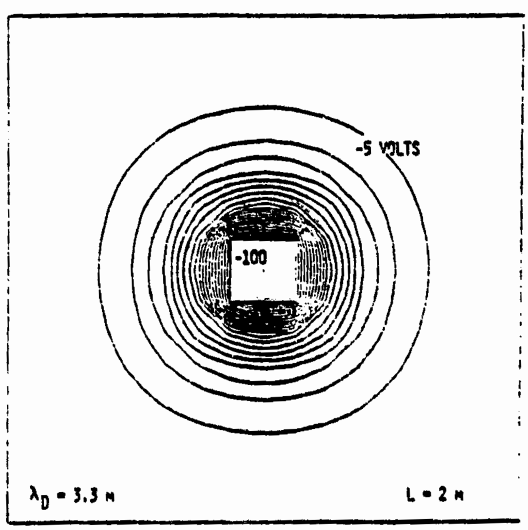

Figure 26. Here the same cube is charged once again to -100 V. This plasma has Debye length of 3.3 meters. The denser plasma leads to more significant shielding, and the potential falloff is steeper near the cube.

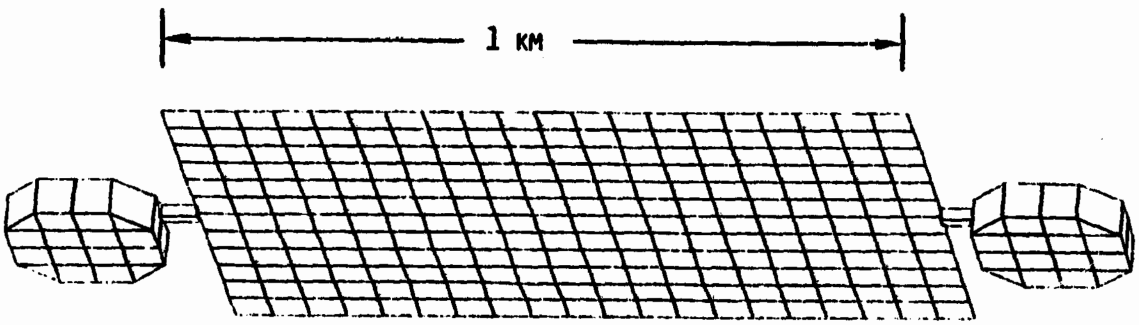

Figure 27. Solar power space station model.