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DEVELOPMENT OF A CONTINUOUS BROAD-ENERGY-SPECTRUM ELECTRON SOURCE*

R. C. Adamo and J. E. Nanevich
SRI International
Menlo Park, California 94025

The primary accomplishment of the laboratory research program described herein has been the development of a practical prototype, large-area, continuous-spectrum, multienergy electron source to simulate the lower energy (≈ 1 to 30 keV) portion of the geosynchronous orbit electron environment. The results of future materials-charging tests using this multienergy source should significantly improve our understanding of actual in-orbit charging processes and should help to resolve some of the discrepancies between predicted and observed spacecraft materials performance.

BACKGROUND

Complex interactions between a spacecraft and the surrounding space environment can cause the deposition and redistribution of significant amounts of electrical charge on the exterior of conducting and insulating surfaces and within exposed dielectric materials (ref. 1).

This naturally occurring phenomenon, known as spacecraft charging, can adversely affect normal system performance in a number of ways. For example, the resulting local external static fields can interfere with the operation of electric-field-sensitive instruments and cause the reattraction and deposition of contaminants on critical thermal control, solar array, and other optical surfaces. More serious effects can occur if the electric fields between adjacent surfaces or within dielectric materials become large enough to produce electrical breakdowns (ref. 2). The electric currents produced by these rapid changes in charge distribution can cause local physical damage to external thermo-optical surfaces and radiate electromagnetic signals of sufficient amplitude to upset or possibly damage onboard electronic systems.

Over the past decade, a substantial effort has been made to increase the available knowledge relating to the causes and effects of spacecraft charging, and the results of numerous theoretical studies, laboratory tests, computer simulations, and limited in-orbit measurements have been published. Unfortunately, the combination of interactions between actual operational spacecraft and the real space environment is too complex to predict accurately or explain many observed or suspected in-orbit spacecraft responses, with confidence, using presently available techniques.

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To date, laboratory simulations of the charging and electrical-breakdown characteristics of typical spacecraft materials have been performed, by most agencies, using conventional monoenergetic, thermionic (hot-filament) electron sources to simulate the lower-energy (less than 40 keV), geosynchronous-orbit electron environment.

Although thermionic sources are ideal for many applications, in general they exhibit several practical disadvantages for spacecraft charging studies, including:

- Cathode contamination--Most thermionic cathodes are readily contaminated by outgassing products from realistic spacecraft material test samples.
- Poor beam uniformity--Achieving a large diameter beam with uniform current density is difficult.
- Limited beam diameter at close range--Expanding the beam from most thermionic sources to cover a large area sample at close range is also difficult.
- Interdependent beam characteristics--In particular, in a simple system, changing the beam current density or profile requires a complex electrostatic lens system and a readjustment of lens and grid voltages.
- Filament illumination--In some experiments, undesirable optical radiation from the heated cathode can alter the responses of the test-sample materials.

Several years ago, SRI International developed an alternative type of electron source, based on the multipactor phenomenon, for use in spacecraft charging studies (ref. 3,4). Although this basic source, shown schematically in Figure 1, also produces a monoenergetic electron beam, it eliminated many of the disadvantages of conventional thermionic systems.

Many independent studies of the charging and discharging properties of spacecraft materials have been performed using monoenergetic electron sources. Although the results of these independent laboratory tests have agreed reasonably well, a number of discrepancies appeared between the test results and actual in-orbit observations of electrical charging and discharge occurrences on operational spacecraft. For example, SRI International discharge detection instrumentation on a DSP satellite and on the P78-2 (SCATHA) satellite (along with a full complement of other spacecraft-charging instruments), has indicated that electrical discharges (and, in some cases, resulting spacecraft anomalies) occur at times when they would not be expected according to the results of laboratory tests. This is not altogether surprising, however, since the theory of dielectric charging predicts that the exact profiles of the internal charge distributions and, therefore, the magnitudes of the internal electric fields are determined by the details of the incident electron energy distribution (ref. 5).

Material charging tests performed using two separate monoenergetic electron guns at different energies have confirmed that, with just two discrete energies, the test results differ significantly from those obtained using a single-energy source (ref. 6,7).

The primary objective of the laboratory research program discussed herein has been to develop a practical prototype, continuous-spectrum, multienergy electron source to simulate more precisely a significant portion of the lower-energy in-orbit electron environment. The results of this work are described below.

BASIC MULTIENERGY ELECTRON SOURCE CONCEPT

If a beam of electrons having an energy of a few tens of keV strikes a thick metal target, a portion of the beam ($\approx 10-20\%$) will be backscattered. The remaining electrons will penetrate to various distances within the material before being stopped. If instead, the target is a sufficiently thin foil, some of the electrons will pass completely through the foil and emerge with reduced energies. This phenomenon has been used to modify the monoenergetic multipactor electron gun to produce a continuous multienergy beam.

Many theoretical and experimental studies have been made of the transmission of electrons through thin metal films (e.g., ref. 8-14). Figure 2 shows typical energy distributions of electrons transmitted through various thicknesses of aluminum and gold films with an incident electron beam energy of approximately 20 keV. For the illustrated range of film thicknesses, each of the transmitted electrons is likely to have lost some of its energy within the film through numerous scattering events. As expected, for a given material, the total energy loss per electron, as well as the percentage of incident electrons totally lost within the film, increases in thicker films as a result of a statistically greater number of scattering events.

Results similar to those in Figure 2 were obtained in a series of tests at SRI. In these tests, small samples of 0.75-, 1- and 2- μm thick aluminum films were mounted across a 50-mm-diameter aperture in a large aluminum plate which replaced the outer accelerating grid of the monoenergetic multipactor source. A simple standard type of retarding potential analyzer consisting of three wire-mesh grids within a cylindrical Faraday cup was used to measure the electron energy spectra.

Figure 3 shows a few examples of "typical" electron energy distributions measured under various conditions in geosynchronous orbit (ref. 15). The top curve in this figure is the expected maximum. In these examples, the in-orbit electron current density decreases monotonically and quite rapidly with increasing energy. In contrast, the electron currents of Figure 2, produced by scattering through foils of uniform thickness, increase to a maximum at an energy somewhat below the incident beam energy (E_0) and then decrease more rapidly to an immeasurably low level at or below E_0 .

Fortunately, this difference in spectral form can be overcome, to a large extent, by using a specially prepared composite foil as illustrated in Figure 4. The first composite foils of this type were prepared in steps by vapor deposition of gold through appropriate masks onto commercially available aluminum film substrates.

The foil illustrated in Figure 4, though not drawn to scale, combined with the spectra in Figure 2, can be used to explain qualitatively the basic composite-foil concept as follows. The portion of a 20-keV incident beam that passes through the substrate alone will emerge with an energy distribution as shown in the 0.74- μm spectrum in Figure 2a. The portion that passes through only one gold layer will enter the substrate with approximately the 0.28- μm spectrum in Figure 2b and will emerge with its electron energies further reduced, thus "filling-in" a lower energy range in the total composite spectrum. Electrons passing through both gold layers as well as the substrate will obviously emerge with even lower energies.

It is, in this way, possible to "tailor" the overall character of the output energy spectrum through an appropriate choice of patterns and thicknesses of additional metal layers on the composite foil. Since the transmitted current density is

significantly lower through the thicker metal layers, the production of a relatively flat or monotonically decreasing output energy spectrum requires that the thicker metalized layers cover a larger relative percentage of the total foil area.—

A major advantage of the multienergy beam production technique described above is that the composite foil is a totally passive device, and therefore, no major modifications of the monoenergetic electron source, other than mounting the foil across the exit aperture, are required for multienergy operation. In addition, the energy spectrum of the source can be readily changed by physically interchanging foils, and, within a certain range, the energy of the overall spectrum can be shifted up or down by changing the energy of the incident beam. The source can also easily be converted for single-energy operation simply by replacing the composite foil assembly with a standard wire-mesh accelerating grid.

The successful results obtained in initial, small-scale tests of the composite foil concept formed a promising basis for the development, on this program, of a more practical, larger-beam-area, multienergy electron gun system. To accomplish this effort, however, it was necessary to devise new techniques for fabricating and mounting the composite foils.

For example, to produce a broad output energy spectrum, a significant fraction of the input beam energy must be absorbed by the foil. Since metal films are relatively poor thermal radiators, the resulting heat is removed mainly by conduction to the mounting plate at the foil edges.

In initial tests with a 20-keV incident beam energy, composite foils mounted across a 50-mm-diameter aperture performed satisfactorily with output current densities of 10 nA/cm² but were readily damaged by excessive heating with current densities 2 to 3 times higher. This problem was subsequently solved by mounting the composite foils between pairs of 0.06-in.-thick perforated aluminum plates that act as heat-sinks for the absorbed power. The holes in these plates are small enough (0.19-in.-diameter) to allow sufficient heat conduction from the unsupported foil areas, and numerous enough (0.25 in. between centers) to provide a 53% exposed foil area when properly aligned. With this mounting arrangement, it became possible to increase the overall transmitted current density by at least a factor of five, with no detectable foil damage. In addition, the protection and support provided by these mounting plates makes handling and installation of the foils considerably easier.

It was originally planned that larger area aluminum foils of this same thickness (0.75 μ m) would be used as the basic composite foil substrate. However, upon careful examination, each of the available unused 50- and 75-mm-square foils was found to contain a number of small pinholes. Subsequent discussions with the manufacturer of these foils, and with another foil supplier, indicated that it is not practical to produce such "large-area" foils of this thickness that are pinhole-free. These pinholes, if not covered by the mounting plates, would allow some uncontrollable, small portion of the incident beam to pass through the foil with little or no reduction in current density or energy.

As a result of this discovery, the electron transmission properties of several alternative thin-film materials, known to be available in larger-area sheets, were measured in an attempt to identify a more suitable pinhole-free substrate material. These measurements were made using a scanning electron microscope (SEM) with incident beam energies ranging from 20 to 40 keV. With this instrument it was possible both to measure total electron transmission ratios and to examine the material samples

for pinholes. It was quickly determined that the available pure metal foils that were thick enough to be pinhole-free were too thick to transmit the required electron currents. However, the materials tested also included several thicknesses of Kapton, Teflon, and Mylar films with thin aluminum, gold, or silver coatings on one or both sides. Several of these materials, normally manufactured for use as thermal-control surfaces on spacecraft, were found to transmit a reasonable fraction of the incident beam current. In addition, these materials are available in large sheets and are considerably less expensive and easier to handle than the previously employed thin metal foils.

The transmission measurements obtained with polymer samples having metallization on one side only were not as repeatable as those obtained with similar samples metallized on both sides. This effect is most probably due to variations in the internal and external electric fields produced by the buildup of charge on and within the exposed dielectric surface. Further tests were therefore confined to polymer films with both sides metallized, since both of the outer metal layers can then be electrically grounded to eliminate external electric fields. It is also likely that the additional thermally conductive path provided by the second metallized surface increases the foil's power-handling ability.

Of the materials tested, Teflon was found to be the most susceptible to thermal damage. Mylar films performed somewhat better, with transmission efficiencies of up to 70% in a 30-keV incident beam, but suffered increasing thermal degradation during relatively short periods of operation with input current densities of a few $\mu\text{A}/\text{cm}^2$.

The candidate substrate materials also included 7.5- μm -thick aluminum-coated and 12.7- μm -thick gold-coated Kapton foils. The metal layer on each side of these foils was approximately 100 nm thick. In a 31-keV beam, these materials transmitted 50% and 25%, respectively, of the 20- $\mu\text{A}/\text{cm}^2$ incident beam current with no noticeable damage.

Doubly aluminized 7.5- μm Kapton film was selected as the most appropriate composite-foil substrate material for the final tests on this program, due both to its higher electron transmission efficiency and because it is less expensive and more readily available than gold-coated Kapton film.

The final composite-foil configuration developed on this program is illustrated in Figure 5. This figure (not drawn to scale) shows the pair of polished aluminum mounting plates that serve as a heat sink for the beam power absorbed by the foil.

The actual metallization pattern, which differs from the pattern in Figure 5, was formed by depositing pairs of almost completely overlapping 10-mm-wide, 0.2- μm -thick silver stripes on a 12-cm-square aluminized Kapton substrate, with approximately 1-mm gaps between each pair of overlapping stripes. This pattern results in 0.4- μm and 0.2- μm silver layers covering approximately 75% and 17%, respectively, of the total foil area, thus leaving approximately 8% of the aluminized substrate exposed.

The measured electron energy spectrum produced by this particular composite foil is shown in Figure 6. A "typical" electron energy spectrum measured during a geomagnetic substorm by the ATS-5 spacecraft in synchronous orbit (ref. 16) is also shown in this figure, for comparison. Since, with an incident electron beam energy of 33 keV, the overall transmission efficiency of this composite foil is approximately 4%, an input current density of 250 nA/cm^2 is required to produce a total output current density of 10 nA/cm^2 .

The largest substrate foil size that could be conveniently processed in the vapor deposition system available for use on this program was a 12-cm square. As a result, the maximum exit diameter of the multienergy beam was limited to approximately 10 cm. The aluminized Kapton film used as the substrate, however, is routinely manufactured in 100-ft rolls, with widths of up-to-3 ft. For most practical applications, the multienergy beam diameter is therefore limited mainly by the size and total current capacity of the input current source (35-cm diameter in the present system) and by the maximum usable dimensions of the metal deposition system used to fabricate the composite foil.

CONCLUSION

The simulation of the medium energy (≈1 to 40 keV) portion of the geosynchronous orbit electron environment for material and spacecraft testing requires a relatively large-area, uniform electron beam with a total current density, at the test object, of 10 nA/cm² or less and, if possible, a realistic distribution of electron energies. This program has resulted in the design and construction of an electron source that meets these requirements.

When operated in a monoenergetic mode, this source produces exit current densities of up to 20 μA/cm² at beam energies up to 40 keV. A control grid permits adjustment of the beam current density over a range from 20 μA/cm² to less than 0.1 nA/cm².

In comparison with other types of electron sources used for spacecraft charging studies, the multipactor source is physically simple and easy to fabricate, produces minimal external electric fields, and is less susceptible to cathode contamination.

In addition, the basic monoenergetic multipactor source produces a large-area electron beam directly, without complex electrostatic lenses, so that the beam characteristics are relatively independent of accelerating voltage.

The major achievement of this program is the further development of the composite scattering foil technique for converting a monoenergetic electron beam to one containing a continuous, broad range of electron energies.

The electron energy spectrum in Figure 6 is just one example of a wide range of spectra that could be obtained using other foil configurations. The illustrated spectrum was produced with an incident 33-keV monoenergetic beam. For a given foil, the overall output energy range can, to some extent, be shifted up or down by changing the input beam energy.

The total output beam current density (i.e., integrated over the entire energy spectrum) is determined by the foil characteristics and by the energy and current density of the input beam. Since a large percentage of the incident beam power is absorbed by the foil, the maximum practical output current density is limited by the ability of the foil and its mounting to dissipate heat. With the present foil-mounting configuration, continuous operation for several hours with an output current density of 40 nA/cm² produced no noticeable foil damage.

The basic monoenergetic multipactor source is ideally suited for conversion to multienergy operation, since the composite-foil assembly can be mounted directly across the large-area exit aperture, thus forming a single compact unit. In prin-

ciple, however, the composite-foil technique could be used with a conventional thermionic electron source by mounting the foil assembly at an appropriate distance from the source in the diverging monoenergetic beam.

SUGGESTED APPLICATIONS AND FURTHER DEVELOPMENT

The basic monoenergetic multipactor electron source can be used in place of a conventional thermionic source in single-energy, material-charging studies and in support of simplified analytical and modeling efforts. The large-area, collimated electron beam produced at the exit aperture makes it possible to irradiate relatively large targets at short range in a small vacuum chamber-test facility.

Although the present source produces a beam of circular cross-section for special applications, it is possible to change the shape of the output beam by placing a mask over the exit aperture or by fabricating a similar system with a noncylindrical geometry. Because of the overall mechanical and electrical simplicity of the multipactor electron source concept, many design configurations are possible and can be fabricated using readily available, basic shop materials.

Earlier experiments at SRI indicate that, with some simple modifications, it should be possible to convert the basic multipactor system from an electron source to an ion source. In these experiments, nitrogen gas was injected at a low rate into the multipactor region between the cathode plates. The gas was thereby ionized by multiple collisions with the oscillating electron cloud, and the resulting positive ions were extracted by reversing the polarity of the high-voltage accelerating power supply. Although few quantitative measurements were made in these early tests, it appears that, with some further development, the basic multipactor system could serve as a practical source of both ions and electrons. In addition to its usefulness in spacecraft charging studies, the multipactor electron or ion source may have applications in a variety of material-processing applications.

The development of the continuous multienergy electron beam generation technique is a major advance in our ability to simulate more realistically the lower-energy, in-orbit electron environment. The results of future materials-charging tests using this multienergy source should significantly improve our understanding of actual in-orbit charging processes and should resolve some of the discrepancies between predicted and observed spacecraft materials performance.

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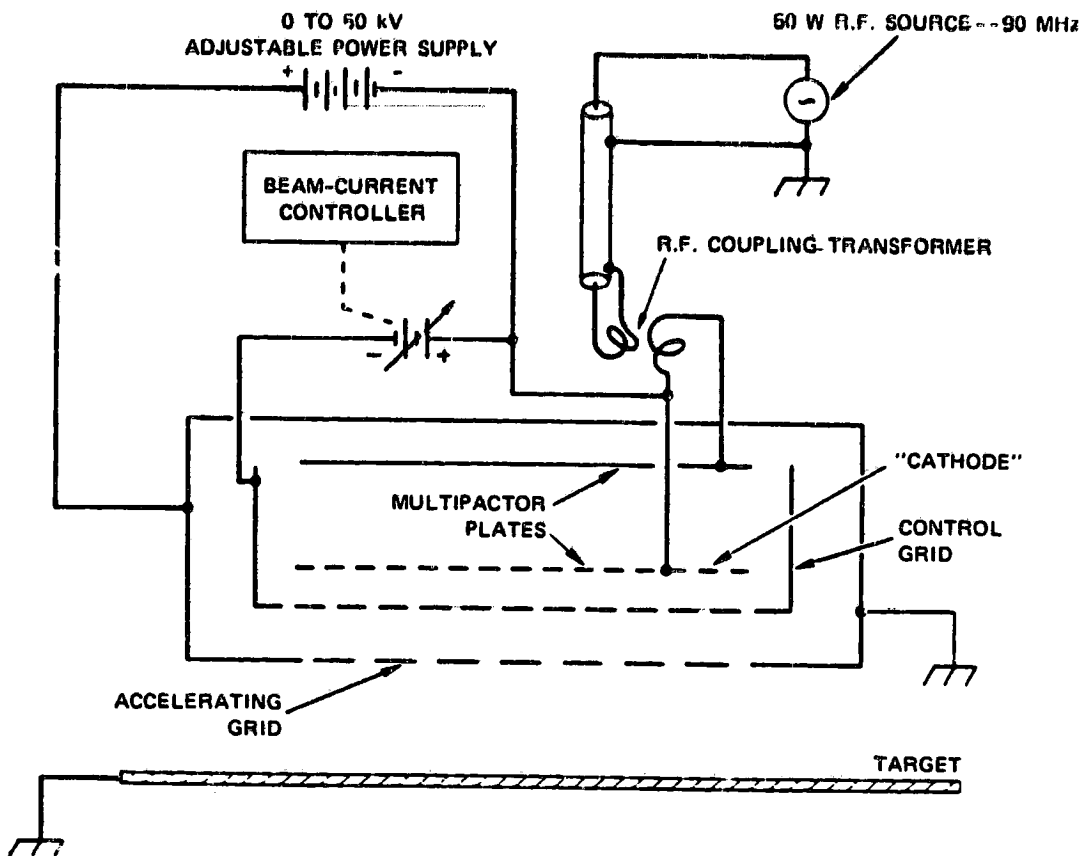


Figure 1. - Present multipactor electron source (schematic).

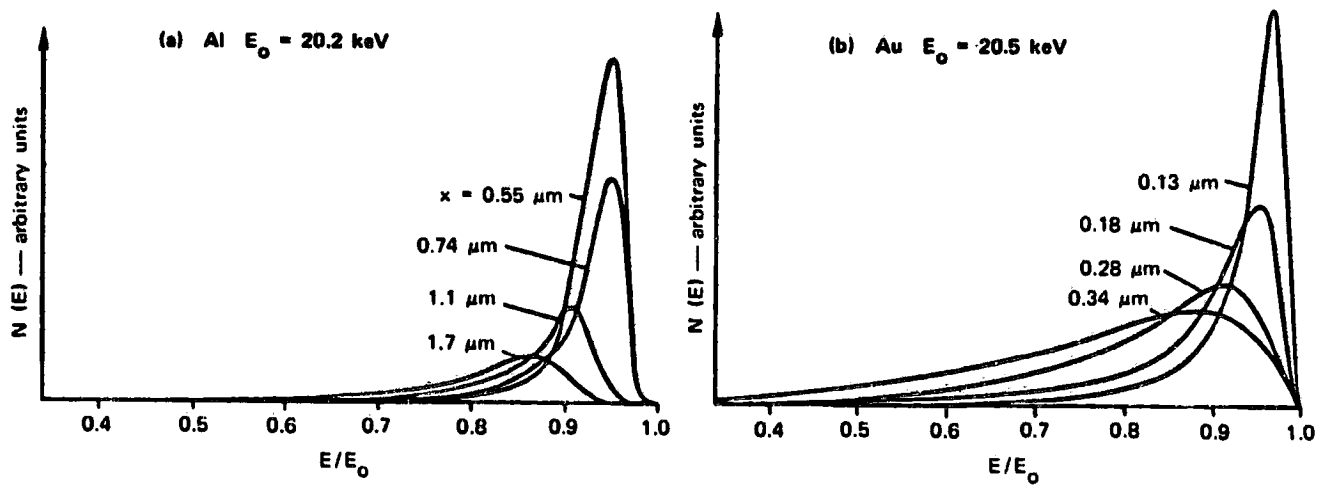


Figure 2. - Energy distributions of electrons transmitted through thin metal films.

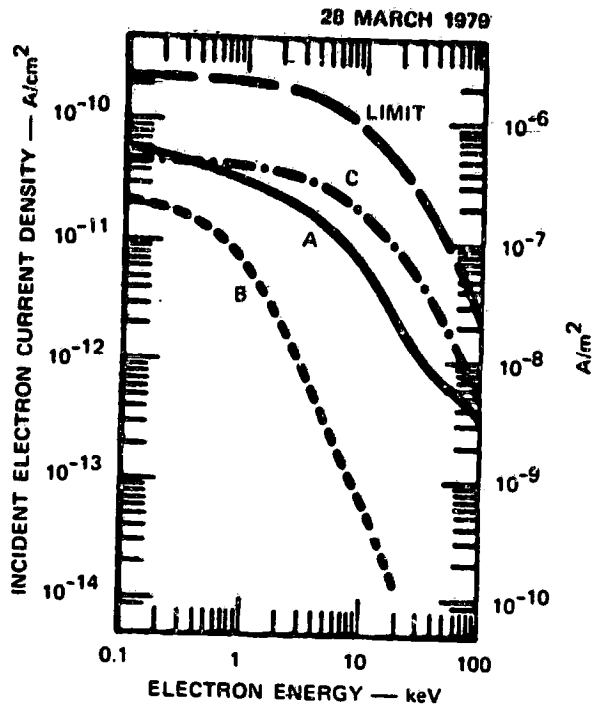


Figure 3. - Typical geosynchronous electron current densities.

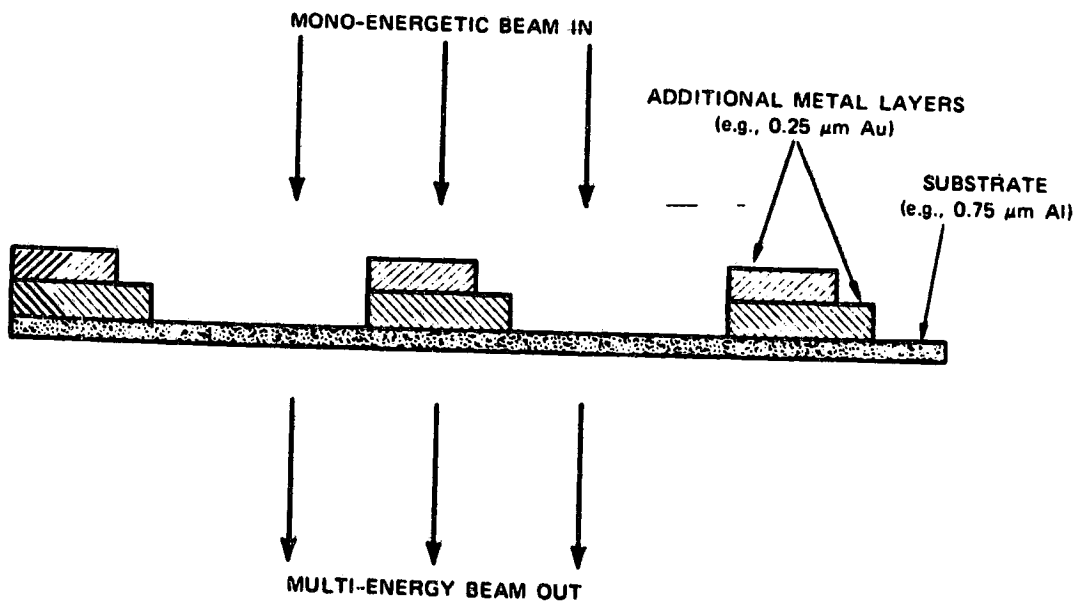


Figure 4. - Composite-foil concept.

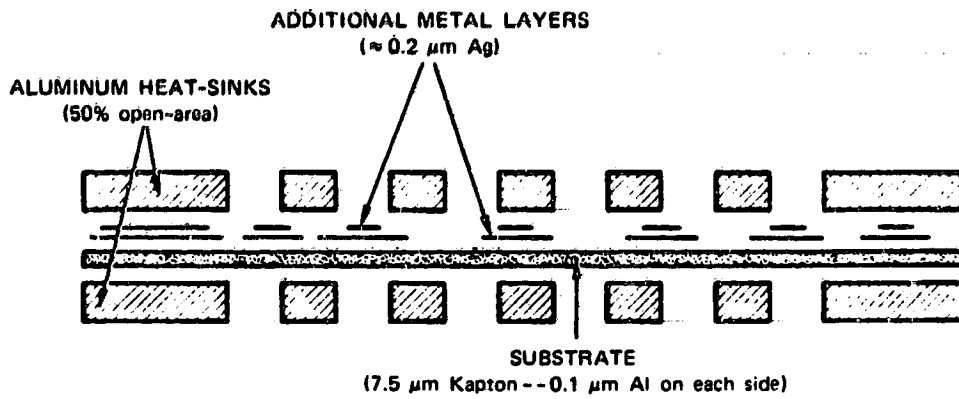


Figure 5. - Multiple-layer composite film.

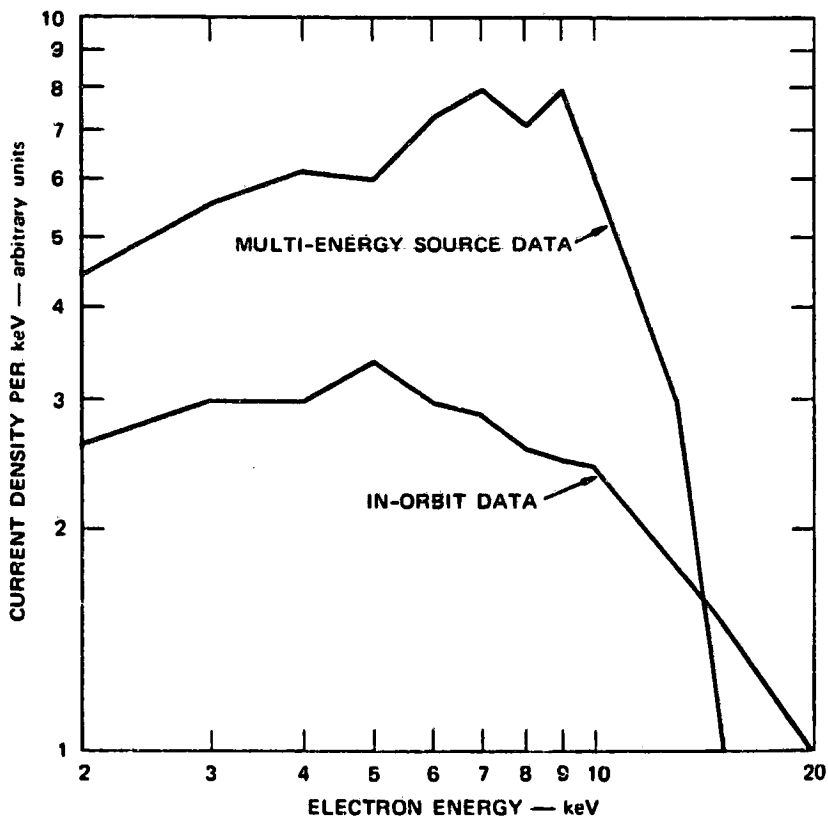


Figure 6. - In-orbit and simulated electron spectra.