The artificial radiation belt created by the July 9 nuclear event has caused serious degradation of the power-generating solar cells in some U. S. satellites. This paper discusses the significant factors relating to this degradation, and describes the effect of high-energy electron radiation on two types of solar cells.

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Effect of the Artificial Radiation Belt on SOLAR POWER SYSTEMS

As a result of the high-altitude nuclear test performed over Johnston Island on July 9, 1962, an intense electron radiation belt has been created. Since this test, several other high-altitude nuclear explosions have been detonated in the U. S. testing program at Johnston Island and also by the U.S.S.R. As a result of the July 9 test, and to some unknown degree the other high-altitude nuclear tests, the radiation at altitudes for earth satellites was much changed both in character and intensity. The electrons in this artificial belt have a sufficiently high energy and density to impair seriously the operation of earth-satellite solar-cell power-generating systems.

Prior to release of this large number of electrons that were geomagnetically trapped in the earth's magnetic field, the solar power-generating capability of earth satellites orbiting in the lower altitudes was severely degraded by the natural (Van Allen) proton radiation belt. On the other hand, for reasonably high altitudes such as the 600-nautical-mile altitude of the ANNA satellite, solar cells protected by only 6 mils of glass were expected to perform with comparatively little degradation for periods of several years. The artificial radiation belt, however, has caused the electron damage to the solar cells to be far more significant than the proton damage for most orbital altitudes.

The mechanism for capture of the electrons has been described by G. F. Pieper in this issue of the *Digest*. The two factors that are significant to the performance of solar cells are the number of particles trapped at a particular altitude and the energy spectrum of these particles. A series of typical energy distributions of the electrons resulting from the fission process in an atomic weapon

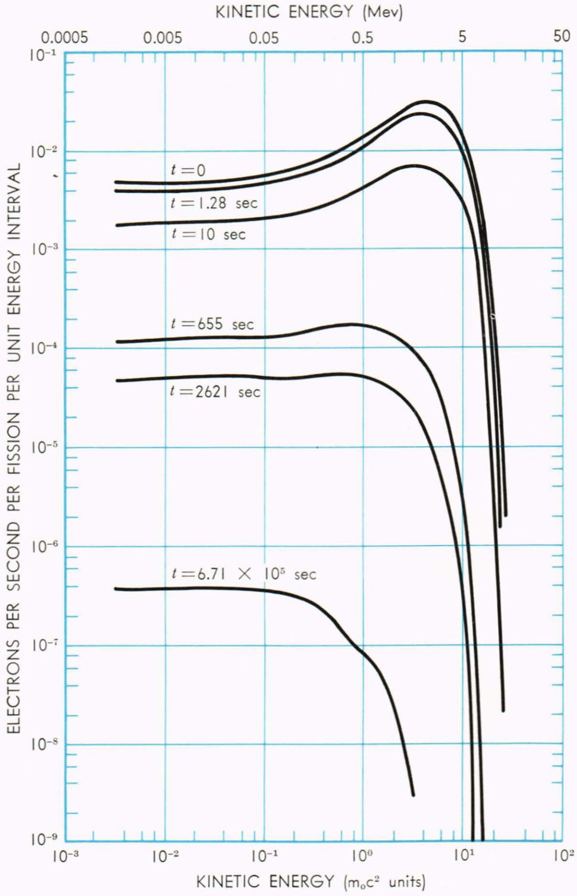

Fig. 1—Time dependence for electrons resulting from fission of uranium.

is shown in Fig. 1.[1]

It will be noted from this figure that the fission spectrum is time-dependent; in particular there are many high-energy electrons emitted promptly. To calculate the energy distribution of the electrons as a function of position in space, it is necessary to know the details of the deployment of the fission fragments and also the distribution in time and direction of the decay electrons. Therefore, there is a considerable uncertainty as to the energy distribution of the trapped electrons.

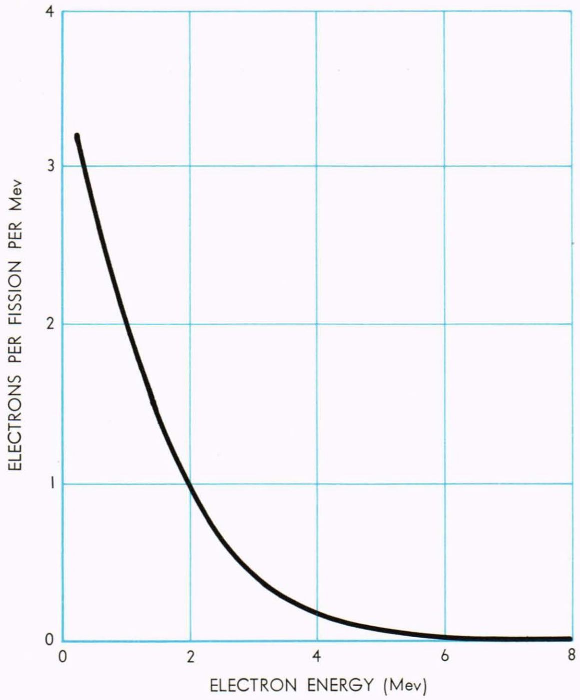

Fig. 2—Fission electron energy spectrum.

As described by Pieper, results from particle counters in several satellites indicate that the energy spectrum of the electrons is represented fairly well by the "fission spectrum" of uranium. An average fission spectrum[2] for the fission of U^{235}, as shown in Fig. 2, is probably a fair representation of the energy spectrum of the captured electrons to which the satellite is exposed. The significance of this spectrum is that it is rich in electrons with energies above 1 Mev. While these electrons cause extensive damage to the solar cells, the cover slide thickness that would be necessary to protect the solar cells from this high-energy radiation would cause an excessive weight for the solar power-generating system.

Effect of Radiation on Solar-Cell Performance

The power for most space vehicles today is generated by silicon solar cells, usually in conjunction with nickel-cadmium storage batteries. The great majority of the solar cells have a positive layer on top of a negative base material (P-on-N solar cell). This type is particularly sensitive to electron radiation. Only one American satellite to date—Telstar—is powered by the solar cells with a negative surface material on a positive base (N-on-P). These N-on-P cells are less sensitive, by a factor of between 10 and 30, to high-energy electron radiation.

In the generation of electric power from light, a photon impinging on the solar cell creates an electron and a hole; these then migrate either toward or away from the *p-n* junction. The potential difference resulting can be used to supply power to an electrical load. The average distance that can be traversed without recombining is called the *diffusion length*; the greater the diffusion length, the more efficient the solar cell. The effect of radiation from either electrons or protons is to introduce imperfections in the crystal structure of the silicon, giving rise to recombination centers and, therefore, a shortening of the diffusion length and a resulting decrease in the efficiency of the solar cell. In Fig. 3 is shown the effect of radiation on the diffusion length for N-on-P solar cells.[3] Also shown is the degradation of short-circuit current as a result of 1-Mev electron radiation for both N-on-P and P-on-N solar cells. The increased resistance to radiation for the N-on-P cells is apparent.

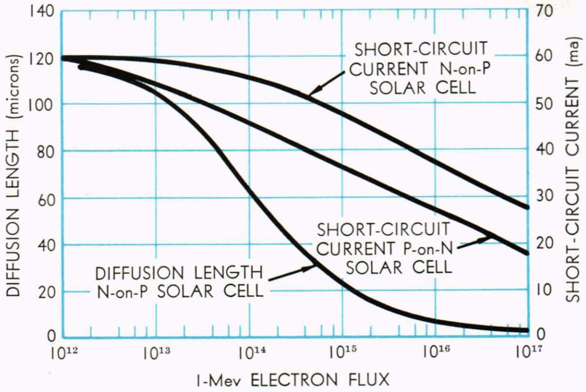

Fig. 3—Effect of electron bombardment on solar-cell characteristics.

The depth to which light penetrates into the

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[1] R. B. Heller, "Energy and Time Beta Ray Spectra of Fission Products of U^{235} by Fission Neutrons and U^{238} by 14 Mev Neutrons," *WSEG Research Memorandum 19,* Weapons Systems Evaluation Group, Washington, D. C.

[2] R. E. Carter, F. Reines, J. J. Wagner, and M. E. Wyman, "Free Antineutrino Absorption Cross Section," *Phys. Rev.* **113**, Jan. 1, 1959, 283.

[3] F. M. Smits, W. Rosenweig, and W. L. Brown, "Report of Solar Cell Work at Bell Telephone Laboratories," *Proc. Solar Working Group Conference*, **1**, Washington, D. C., Feb. 27, 1962, 9-1 to 9-29.

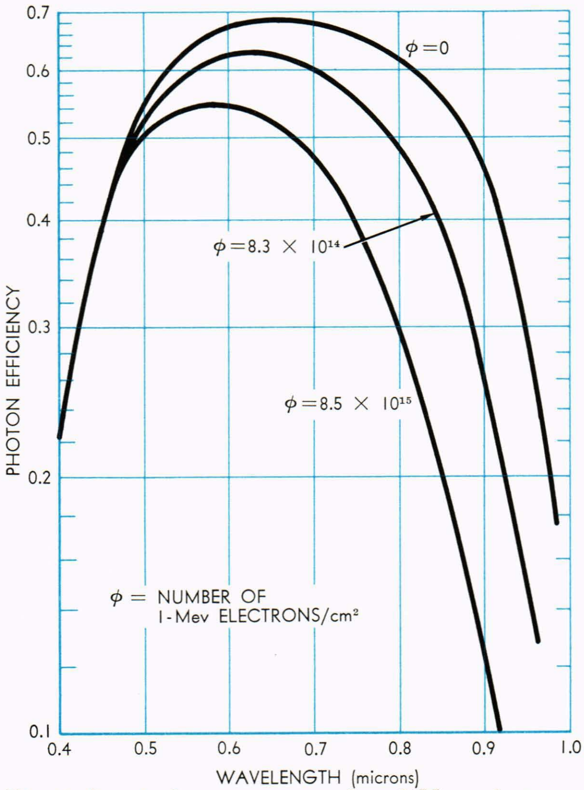

Fig. 4—Spectral response under 1-Mev electron bombardment.

solar cell is dependent upon the frequency of the light, the lower frequencies penetrating to a much greater depth. For natural sunlight, the highest frequency to which the solar cells respond (the near ultraviolet) will penetrate a few microns into the cell; the longest wavelengths (in the near infrared) will penetrate to depths of the order of 100 microns. As a result, the power generated from blue wavelengths occurs close to the surface of the cell, and that generated by the red wavelengths is proportionately greater at the greater depths. Since the effect of radiation damage is to shorten the diffusion length, the power generated from blue wavelengths collected close to the *p-n* junction is virtually unaffected by even extensive shortening of the diffusion length. Conversely, the red wavelengths, since they create electron hole pairs at considerable depths in the silicon, will be most affected by a decrease in the diffusion length. Figure 4 illustrates the effect of radiation damage on the spectral response of the cell.[4]

Electrons with energies below 0.2 Mev have virtually no effect on cell efficiency. The damage effect then increases with increasing energy for electrons up to an energy of 1 Mev, above which the damage due to the electrons remains virtually constant with increasing energy.

Design of the Solar-Cell Experiments

The Transit 4B and TRAAC satellites were launched simultaneously into the same orbit from Cape Canaveral on Nov. 15, 1961.[5] Each satellite contained experiments to determine the performance of solar cells in the space environment.[6] For monitoring this performance, the Transit employed a single solar-cell panel consisting of 20 series-connected, "blue-sensitive" P-on-N gridded solar cells. Each cell was 1 × 2 cm and was covered with 6 mils of micro-sheet glass having an anti-reflecting coating and blue reflecting filter. The solar cells were operated at approximately 0.2 volt per cell into a 75-ohm resistance, thereby providing a voltage measurement essentially proportional to the short-circuit current.

The TRAAC satellite employed four separate solar panels, each with two cells in series. These were also P-on-N solar cells covered by 6-mil micro-sheet glass with blue-reflecting filter and anti-reflecting coating.

The temperature of the solar panels was monitored on both satellites. It is estimated that the temperature variations encountered when reading solar-cell performance at near zero angles of incidence of the sun result in an error of less than 1% and can therefore be ignored.

To determine solar-cell performance it is necessary to know the attitude of the solar cells relative to the sun. Since Transit 4B has its symmetry axis stabilized along the local direction of the earth's magnetic field, it is possible to predict the attitude of a solar panel that is perpendicular to this axis.[7] Measurements were made on Transit when the sun was illuminating the panel at nearly normal incidence.

The TRAAC satellite employed independent solar attitude detectors to determine the position of the test solar panels relative to the sun.[6] As with Transit 4B, measurements to determine solar-cell degradation were confined to those cases when the sun illuminated the solar cells at nearly normal incidence.

Since the earth is in a somewhat elliptical orbit about the sun, the satellite will undergo some change in its output due to the variation in solar

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[4] F. M. Smits, K. D. Smith, W. L. Brown, "Solar Cells for Communication Satellites in the Van Allen Belt," *J. Brit. Inst. Radio Engrs.*, **22,** Oxford, England, Aug. 1961, 161–169.

[5] R. E. Fischell, "The TRAAC Satellite," *APL Technical Digest*, **1,** Jan.–Feb. 1962, 3–9.

[6] R. E. Fischell, "Solar Cell Experiments on the TRANSIT and TRAAC Satellites," *Proc. Solar Working Group Conference*, **1,** Washington, D. C., Feb. 27, 1962, 6-1 to 6-27.

[7] R. E. Fischell, "Passive Magnetic Attitude Control for Earth Satellites," *8th Annual National Meeting of the American Astronautical Society*, Washington, D. C., Jan. 16, 1962, paper 62-8.

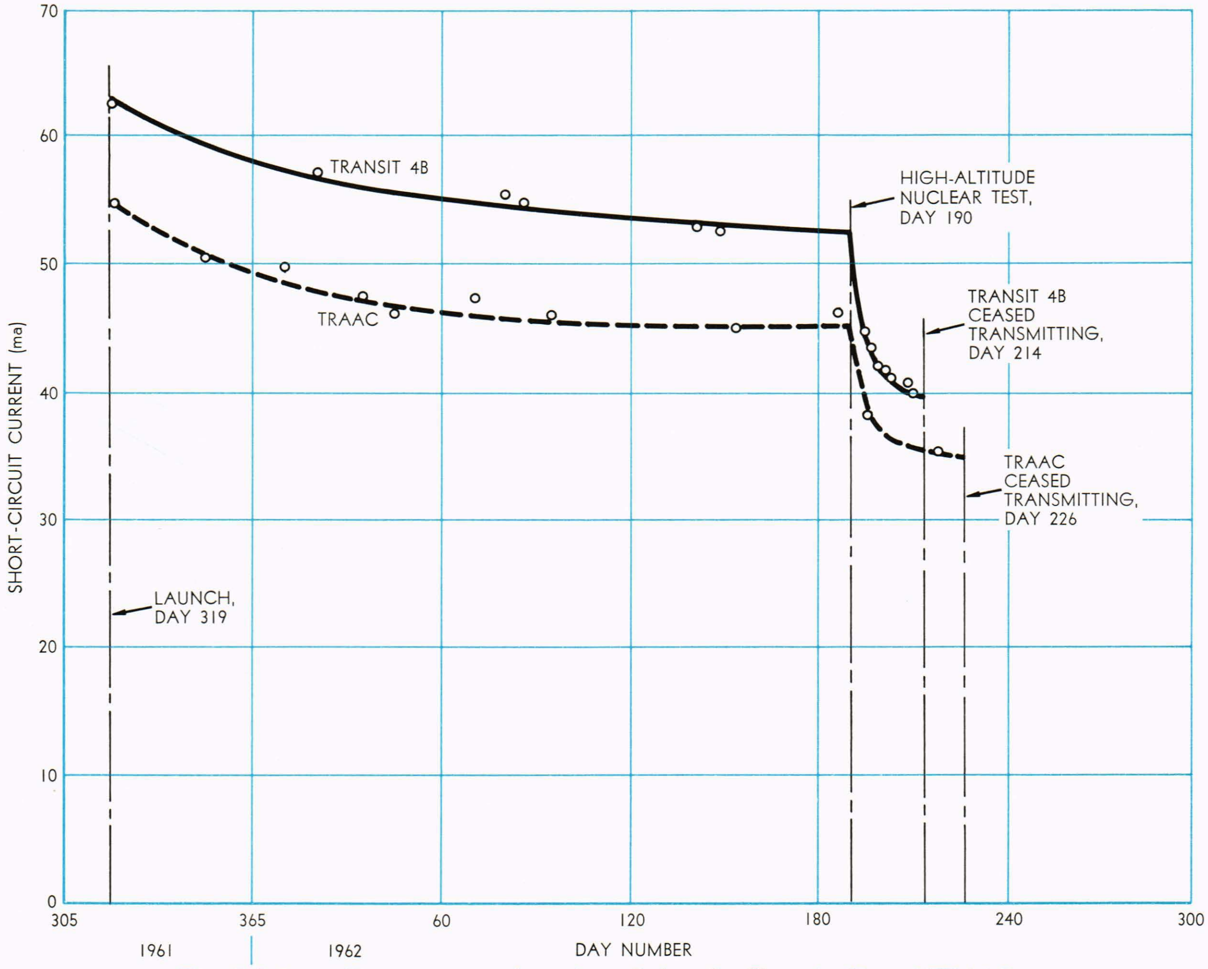

Fig. 5–Solar-cell output as a function of time for Transit 4B and TRAAC.

intensity at the earth. This variation amounts to 6.8% in a 6-month period and should be taken into account when attempting to determine accurately the solar-cell output over extended periods of time.

Results from the Orbiting Satellites

Figure 5 shows the short-circuit current as a function of time for Transit and TRAAC; this curve has been normalized for a solar constant of 140 mw/cm^2. In a period of 236 days from the launch date, until July 9, 1962, Transit 4B solar cells showed a deterioration of approximately 17%. During the same period of time, the −Y solar panel of TRAAC showed a deterioration of approximately 18%. In a 20-day period after the high-altitude nuclear test, Transit showed a deterioration of 22%. In a period of 28 days after the July 9 test, the TRAAC −Y solar panel showed a deterioration of 22%. For a 5-day period after the explosion, the Transit solar panel showed a decrease of 16%; the four TRAAC panels showed decreases as follows: −X, 16%; +Y, 18%; −Y, 12%; and +Z, 15%. For both Transit and TRAAC, the deterioration was more rapid at first, then slowing slightly as is expected for radiation damage to solar cells under a constant or decreasing intensity flux of particles.

As a result of the decrease in the power generated by the satellite's power-system solar cells, Transit 4B ceased transmitting on Aug. 2, 1962. The last transmission was received from TRAAC on Aug. 14.

Figure 6 shows the dependence of the outer-space short-circuit current on 1 Mev electron bombardment for "blue-sensitive" P-on-N solar cells as obtained from work performed at the Bell Telephone Laboratories.[3] The Transit data were fitted to this curve by the following procedure. Data received from the orbiting satellite immediately after launch were normalized to the flat portion of the curve; the short-circuit current extrapolated for Day 190 (July 9) was fitted onto the curve; and the short-circuit current measured on Day

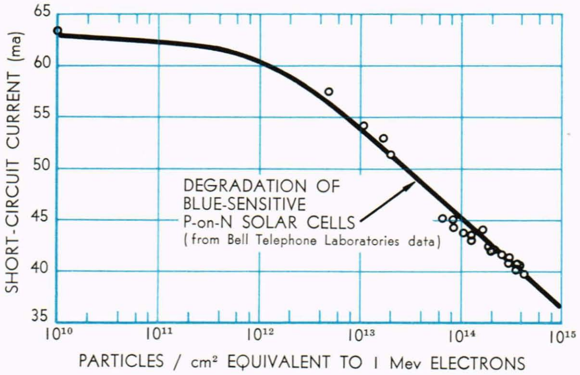

Fig. 6—Degradation of Transit 4B solar cells.

212 was fitted onto the curve. One can then compute the average particle flux level both before and after the high-altitude nuclear test required to produce this degradation. The result shows that before Day 190 the particle flux was equivalent in damage to 8.5×10^{10} 1-Mev electrons/cm²/day. After the high-altitude nuclear test, the curve indicates a damage equivalent to 1.9×10^{13} electrons/cm²/day, with an energy of 1 Mev. This is an increase by a factor of 225 in the particle flux effective in damaging solar cells protected by 6 mils of glass. The position of the other data points obtained from the Transit solar cells can then be determined, assuming the average particle flux levels as stated above for the periods before and after the nuclear test.

Although electron radiation levels at very low altitudes (below 150 miles) did decrease rapidly,* it appears from satellite-borne electron counters and from these solar-cell measurements that the radiation level at satellite altitudes (~500 miles) remained fairly constant after the first day. Figure 7 shows in detail the degradation of the Transit 4B solar cells after July 9. Two curves have been drawn. The first is for a constant particle flux of 1.9×10^{13} particles/cm²/day. A better fit to the data is given by assuming higher initial flux which then tapers off to a steady level. Let us assume an integrated flux on the satellite given by $\phi = 1.72 \times 10^{13}t + 4 \times 10^{13}\ (1-e^{-2t})$ particles/cm² where t = time in days from the day of the burst. This expression represents a steady flux of 1.72×10^{13} particles/cm²/day, plus an *initial* flux rate of approximately five times that value that decreased exponentially with a time constant of 12 hr. The fact that the radiation levels were distinctly higher immediately after the explosion is clearly borne out by Ariel satellite data.*

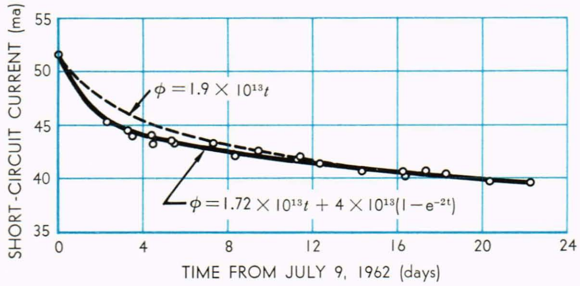

Fig. 7—Transit 4B solar-panel performance after the July 9, 1962, nuclear event.

The value of 1.72×10^{13} particles/cm²/day incident upon the solar cells is higher than the omnidirectional flux given by W. N. Hess for the Transit 4B/TRAAC orbit that was stated as 4.5×10^{12} particles/cm²/day. These two figures are in reasonable agreement. The somewhat greater flux deduced from solar-cell measurements could be due to:

1. The particle flux levels in the Transit/TRAAC orbit might be higher than computed from the composite counter data from several satellites.
2. The solar cells monitored may be more radiation-sensitive than a "typical" blue-sensitive P-on-N solar cell.
3. The radiation caused a darkening of the micro-sheet glass cover slide and/or the adhesive bonding the slide to the glass.

Agreement of Transit 4B and TRAAC solar-cell degradation figures indicates that, whatever the cause, radiation damage to P-on-N solar cells in this orbit through the artificial radiation belt is most severe.

The ANNA satellite, launched Oct. 31, 1962, includes several experiments on the radiation susceptibility of N-on-P and P-on-N solar cells with various thicknesses of cover slides. As a result of these experiments we will be better able to predict the effectiveness of the protection that can be gained simply by increasing the thickness of the solar-cell cover slides. Preliminary results to date indicate the following significant results:

1. Degradation of solar cells on the satellite's equator appears to be greater than that of the cells on the satellite's polar faces.
2. Degradation of P-on-N solar cells on the polar faces was measured to be 24% in 40 days in orbit.
3. Degradation of P-on-N cells with 30-mil sapphire protection was 7% in 40 days.
4. Degradation of N-on-P cells with 30-mil sapphire protection was 2.3% in 40 days.
5. There was no measurable degradation of the gallium arsenide solar cells on the satellite's polar faces.

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* Private communication from Dr. A. P. Willmore, University College, London, England.

The explanation of the first result is that, since the ANNA satellite is magnetically stabilized, the solar cells at the poles, with their surfaces perpendicular to the local magnetic field direction, are encountering a lower flux rate than those cells whose surfaces are parallel to the magnetic field direction. The result of (2) indicates that the radiation level has decreased by a factor of 6 since July 9. Items (2) and (3) indicate that there are fewer electrons above 1 Mev than expected for a fission spectrum. Item (4) verifies the increased radiation resistance of N-on-P solar cells.

Effect on Satellite Solar-Power Systems

The radiation belt has a far-reaching effect on the use of solar cells for space power systems. Although the new level of radiation has created a serious difficulty, the problems in utilizing solar power systems for earth satellites can be solved. In Fig. 8 is shown the expected degradation for solar cells on a polar-orbiting satellite at a 600-nautical-mile altitude assuming that the current level of radiation is maintained. One answer to the problem of using a solar-cell power system for extended-life satellite systems is to have a considerably greater initial power-generating capability than is needed to supply the electrical loads. For example, if the satellite power requirements are less than 48% of the original solar-cell power-generating capability, it should be possible to achieve a 5-year life in the present radiation environment.

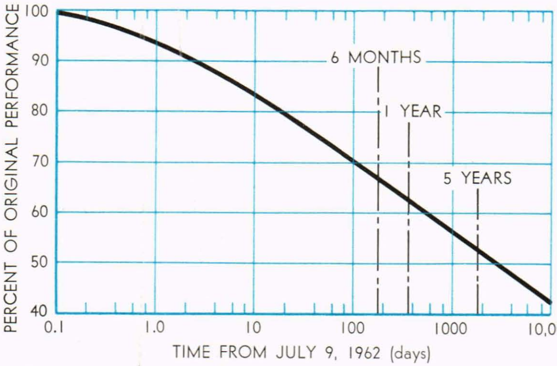

Fig. 8—Solar-cell performance as a function of time for a polar-orbiting satellite at 600-nautical-miles altitude (based on the radiation levels encountered in Dec. 1962).

A second solution to the problem might be to employ the N-on-P type of solar cell that is basically less radiation-sensitive. Using these cells, a factor between 20 and 50 of increased radiation resistance can be obtained. This does not mean, however, that one can use 1/20 as many solar cells to supply the satellite's electrical load. In fact, to supply a specified power-generating capability for a 5-year lifetime at the present radiation level requires approximately 70% of the number of N-on-P cells as compared with the P-on-N type. The principal advantage of the N-on-P cells is this: if the satellite uses as many of these cells as it would P-on-N cells, a 5-year satellite life could be achieved even if the radiation level were increased by a factor of 20 due to additional testing of high-altitude nuclear weapons.

A third solution may be to provide heavy shielding to the solar cells to prevent the energetic particles from impinging on the silicon. Preliminary results from ANNA show that 30 mils of sapphire—equivalent to 50 mils of quartz—offers considerable protection for solar cells in the current radiation environment. This shielding thickness prevents all electrons with the energies below 1 Mev from damaging solar cells.

A combination of a large initial power margin, N-on-P cells, and increased shielding for the solar cells will probably allow a solar-power-generating system to operate for useful lifetimes of 5 years and more even if the present radiation levels are considerably increased.

Conclusions

As a result of the high-altitude nuclear explosion over Johnston Island, an intense electron radiation belt has been trapped in the earth's magnetic field. This belt can cause silicon solar cells to deteriorate at a much greater rate than was previously expected as a result of protons in the natural Van Allen radiation belt. At the altitudes of instrumented satellites, the electron radiation belt does not appear to be diminishing at a rate fast enough to offer relief from this new environment in the near future. To provide a satellite solar-cell power-system with a long-life capability, it will be necessary to provide a large margin of over-design in the initial power-generating capability of the solar power system. The use of N-on-P solar cells will have a significant effect in increasing the life of the satellite's power-generating system. The use of thick cover slides for the solar cells will result in a decrease in the rate of degradation. The extent of this protection cannot be accurately determined until the energy spectrum of the trapped particles is better defined. Direct measurements of the effectiveness of various shield thicknesses are being obtained from the ANNA satellite.*

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* The author wishes to acknowledge the assistance of Dr. J. W. Teener, APL, for performing the computations necessary to obtain the solar-cell performance data presented herein.