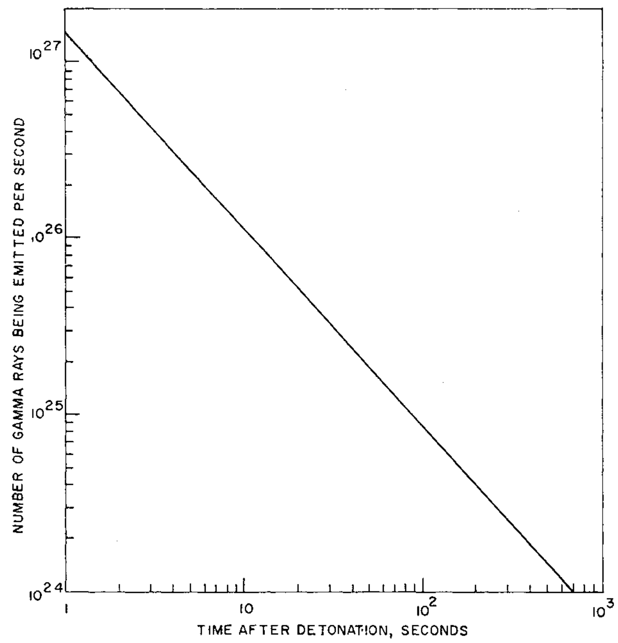


**Fig. 3 Total gamma ray inventory in radioactive cloud following detonation of 20-MT weapon (assumes 50% of energy due to fission; adapted from Ref. 11)**

increment above sea level in centimeters, and $R_{ijkl}$ is distance in centimeters from detector to cloud increment (see Fig. 1)

The factor $1.602 \times 10^{-8}$ in the foregoing equation results from the fact that 1 rad is defined as 100 erg/g of radiation energy dissipated in any irradiated material and that 1 Mev $= 1.602 \times 10^{-6}$ erg.

### Results and Discussion

Fig. 3 shows a typical result obtained using the analytical model. In this case, a 20-MT weapon, half of whose energy yield was due to fission, was detonated 7000 ft above ground. The elevation at ground level was taken as 6000 ft above sea level. No prevailing winds were assumed. The annular widths and heights (Fig. 1) were assigned a value of 100 m.

The effect that variation in air density has on the amount of radiation seen by the detector is quite apparent, as evidenced by the asymmetry of dose rate above and below the cloud center at $T + 4$ min.

Fig. 4 was generated, using the Bendix G-15 computer, in approximately 3.5 hr of computing and readout time. More accurate results could be obtained using a faster computer, dividing the cloud's volume into smaller annuli.

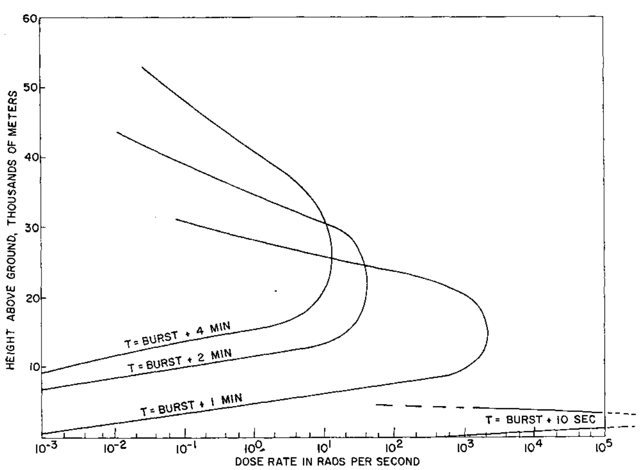


**Fig. 4 Radiation dosage at discrete times and elevations following a 20-MT air burst ($H_{burst}$ = ground = 7000 ft; ground = 6000 ft above sea level)**

### References


1 Glasstone, S. (ed.), *The Effects of Nuclear Weapons* (U. S. Government Printing Office, Washington, D. C., 1962), pp. 10, 34, 36, 689.

2 Kaplan, A. L., "Investigating radiation effects on electronic devices," Aerospace Eng. **21**, 40–50 (July 1962).

3 Clarke, J. W. and Hanscome, T. D., "Radiation pulses and electronics," Nucleonics **18**, 74–78 (September 1960).

4 Kudroff, M. J., "The first Titan hardened facilities," Aerospace Eng. **20**, 10–12 (June 1961).

5 Anderson, A. D., "The NRDL dynamic model for fallout from land-surface nuclear bursts," U. S. Navy Research Dev. Lab. TR-41D (April 5, 1960), pp. 22, 32.

6 Kerr, T. B. and Walton, R. B., "Results obtained using an IBM 704 program for computing $U^{235}$ fission-product populations, activities, and powers," Air Force Special Weapons Center Rept. TN-59-19 (August 1959).

7 Gamble, R. L., "Prompt fission gamma rays from uranium 235," doctoral dissertation, Univ. Texas, Austin, Texas (June 1955).

8 Blizard, E. P., "Nuclear radiation shielding," *Nuclear Engineering Handbook*, edited by H. Etherington (McGraw-Hill Book Co. Inc., New York, 1958), 1st ed., pp. 7–62.

9 Rockwell T., III, *Reactor Shielding Design Manual* (McGraw-Hill Book Co. Inc., New York, August 1959), p. 420.

10 "Pocket data for rocket designers," Bell Aircraft Corp. (June 1958).

11 Way, K. and Wigner, E. P., "The rate of decay of fission products," Phys. Rev. **73**, 1318 (1948).


---

# Solar Cell Performance in the Artificial Radiation Belt


Robert E. Fischell*

*The Johns Hopkins University, Applied Physics Laboratory, Silver Spring, Md.*



**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. The electrons in this artificial belt have a sufficiently high energy and density to impair seriously the operation of solar cell power generating systems. Special solar cell panels on the Transit 4B and TRAAC satellites have shown a 22% decrease in output in a period of approximately 25 days after the high altitude nuclear test. Using solar cell data obtained from Transit 4B and TRAAC in conjunction with direct radiation measurements from other satellites, it is possible to estimate the degradation of solar power generating systems for various satellite orbits.**


### Introduction

THE Transit 4B and TRAAC satellites were launched into the same orbit from Cape Canaveral, Fla., on November 15, 1961. The Transit 4B and TRAAC satellites each contained experiments to determine the performance of solar cells in the space environment. Over a period of 236 days, from launch until July 9, 1962, performance of these solar cells indicated a damage rate that was consistent with present knowledge of the proton flux levels of the inner Van Allen radiation belt. As a result of the high altitude nuclear weapon test of July 9, 1962, the radiation at altitudes of great interest for earth satellites was changed vastly as to both its character and its intensity. As a result of the explosion, a high flux rate of energetic electrons (in the energy region above 100 kev) was more or less permanently trapped at altitudes from as low as 200 miles to as high as 12,000 miles and possibly beyond.

### Design of the Solar Cell Experiments

For monitoring the performance of solar cells in the space environment, the Transit 4B satellite employed a single solar

Presented at the ARS Space Power Systems Conference, Santa Monica, Calif., September 25–28, 1962.

* Project Supervisor, Space Power Systems. Member ARS.

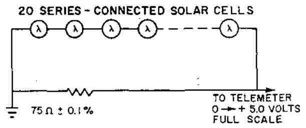


**Fig. 1 Experimental solar cell circuit for the Transit 4B satellite**

cell panel consisting of 20, series-connected, "blue-sensitive" *P*-on-*N*, gridded solar cells. The circuit used for telemetering the performance of these solar cells is shown in Fig. 1. Each cell was 1 × 2 cm and was covered with 6 mils of microsheet glass having an antireflecting coating and blue reflecting filter. These cells were manufactured in the summer of 1961 by Heliotek Corporation. The solar cells were operated at approximately 0.2 v/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, using the circuit shown in Fig. 2. These cells were similar to those used on Transit 4B except that they were manufactured by Hoffman Semiconductor Division during the fall of 1961. The solar cells were covered by 6 mils of microsheet glass with blue-reflecting filter and antireflecting 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 result in an error of less than 1% and therefore can be ignored.

To determine the performance of the solar cell, it is necessary to know the attitude of the solar cells relative to the sun. Since the Transit 4B satellite 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.[1]

It is estimated that, for a magnetically stabilized satellite, a solar panel whose face is perpendicular to the alignment axis of the vehicle will have its attitude determined relative to the sun with an angular accuracy of approximately 3°. This angular measurement accuracy is sufficient for measurements on the solar panels with the sun illuminating them at nearly normal incidence. An angular attitude error at normal incidence of 8° would provide an error in the measurement of panel output of only 1%. Therefore, to obtain the best results, measurements were made on the Transit 4B satellite 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.[2] As with the case of the Transit 4B satellite, 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 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

Fig. 3 shows the short circuit current as a function of time for Transit 4B and TRAAC satellites. This curve has been normalized for a solar constant of 140 Mw/cm$^2$. In a period of 236 days, from the launch date (November 15, 1961) until July 9, 1962, the Transit 4B solar cells showed a deterioration

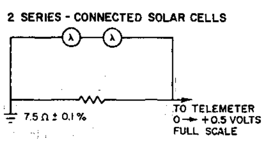


**Fig. 2 Experimental solar cell circuit for the TRAAC satellite**

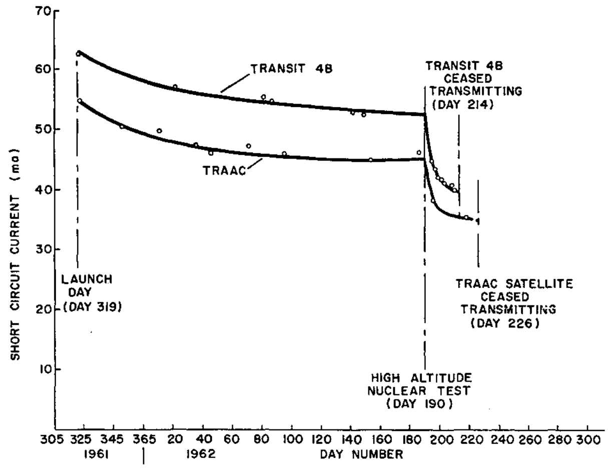


**Fig. 3 Solar cell output as a function of time for Transit 4B and TRAAC**

of approximately 17%. During the same period of time, the $-Y$ solar panel of the TRAAC satellite showed a deterioration of approximately 18%. In a 20-day period after the high altitude nuclear test, the Transit 4B satellite 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 five-day period after the explosion, the Transit 4B solar panel showed a decrease of 16%; the four TRAAC panels showed decreases as follows: $-X$, 16%; $+Y$, 18%; $-Y$, 12%; $+Z$, 15%. For both Transit 4B and TRAAC satellites, the deterioration was more rapid at first and then slowed slightly as is expected for radiation damage to solar cells under a constant or decreasing intensity particle flux.

As a result of the decrease in the power generated by the satellite's power system solar cells, the Transit 4B satellite ceased transmitting on August 2. The last transmission was received from the TRAAC satellite on August 12.

Fig. 4 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 4B data were fitted to this curve by the following procedure:

1) Data received from the orbiting satellite immediately after the launching were placed at the start of the curve.

2) The short circuit current extrapolated for July 9 (day 190) was fitted onto the curve.

3) The short circuit current measured on day 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

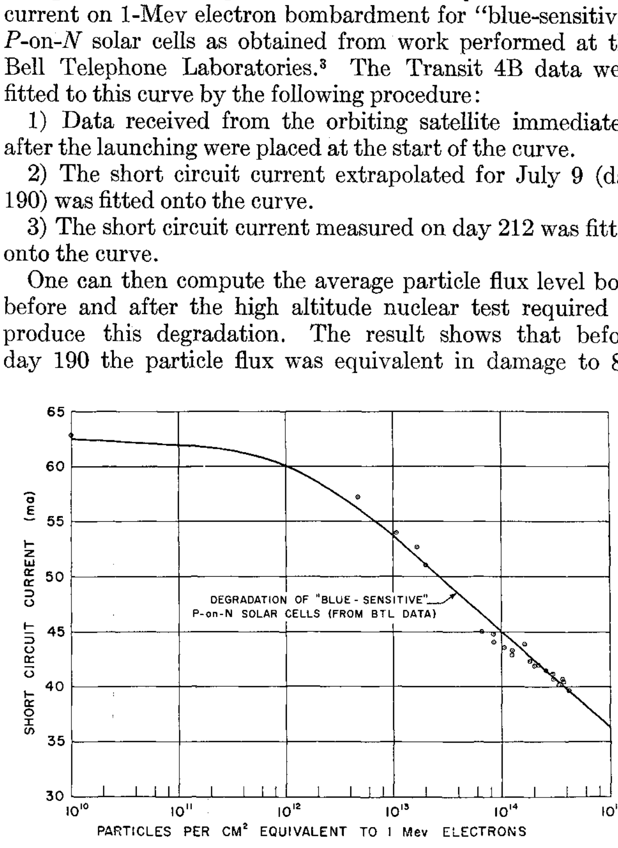


**Fig. 4 Degradation of Transit 4B solar cells**

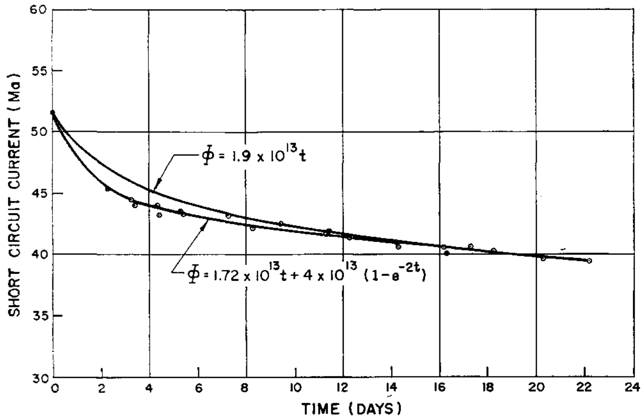


**Fig. 5 Transit 4B solar panel performance after July 9, 1962**

$\times 10^{10}$, 1-Mev electrons/cm$^2$/day. After the high altitude nuclear test, the curve indicates an average of $1.9 \times 10^{13}$ particles/cm$^2$/day equivalent in damage to 1-Mev electrons. 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 4B solar cells can then be determined, assuming the average particle flux levels as stated previously for the periods before and after the nuclear test. From the curve, it can be seen that the radiation intensity to which the satellite was exposed appeared reasonably constant both before and after July 9. One might suggest that in the first few days after the explosion the radiation was somewhat higher (hence several data points below the curve initially), but the rate of decrease after that time appears to be very small. Although electron radiation levels at very low altitudes (below 150 miles) did decrease rapidly,[4] it appears from satellite-borne electron counters and from these solar cell measurements that the radiation level at satellite altitudes (on the order of 500 miles) is remaining fairly constant.

Fig. 5 shows in detail the degradation of the Transit 4B solar cells after July 9. Two possible curves have been drawn from the data points. The first curve is for a constant particle flux of $1.9 \times 10^{13}$ particles/cm$^2$/day. A better fit to the data is given by assuming higher initial flux, which then tapers off to a steady level. Assume an integrated flux on the satellite given by

$$\phi = 1.72 \times 10^{13}\, t + 4 \times 10^{13}\, (1\text{-}e^{-2t}) \text{ particles/cm}^2$$

where $t$ = time in days. This expression represents a steady

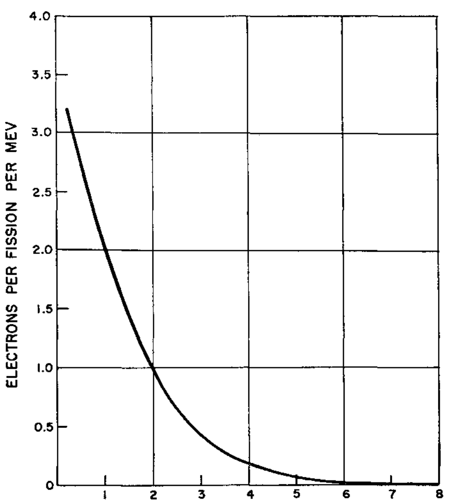


**Fig. 6 Fission electron energy spectrum**

flux of $1.72 \times 10^{13}$ particles/cm$^2$/day plus an initial flux rate of approximately five times that value which 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.[5]

The value of $1.72 \times 10^{13}$ particles/cm$^2$/day incident upon the solar cells is higher than the omnidirectional flux given by W. N. Hess for the Transit 4B/TRAAC orbit which was stated as $4.5 \times 10^{12}$ particles/cm$^2$/day. There could be a combination of several possible causes for this discrepancy:

1) The particle flux levels in the Transit 4B/TRAAC orbit might be higher than computed from counter data.

2) The solar cells may be more radiation sensitive than a "typical" blue-sensitive *P*-on-*N* solar cell.

3) The radiation caused a darkening of the microsheet glass cover slide and/or the adhesive bonding the slide to the glass.

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

The effectiveness of shielding the solar cells depends on the spectrum of the electrons captured in the artificial radiation belt. One would expect that, since the electrons were created by a fission process, the energy spectrum would be typical of that process. Fig. 6 shows the fission beta spectrum of $U^{235}$ from thermal neutrons.[6] From this curve, it can be seen that a large proportion of the electrons are of energies above 1 Mev.

To shield effectively against 1-Mev electrons, one requires approximately 30 mils of sapphire or 60 mils of quartz. If, in fact, the electrons captured in the artificial belt have the distribution shown in Fig. 6, one would not expect a significant improvement by using a shield thickness comparable to only 60 mils of quartz. Although results from Telstar and other satellites indicate that the radiation has approximately the fission energy spectrum, there is still some uncertainty about this point. The uncertainty is due mostly to the fact that the fission beta spectrum is time-dependent, and therefore the manner in which the particles became captured may have caused a deviation from the fission spectrum of Fig. 6. Attitude detectors on TRAAC with 125 mils of quartz showed a decrease in output of not more (and most probably less) than 7.8% in the period from day 95 to day 195, when the Transit 4B solar panel showed a decrease of 21%. From this, one might infer that there might be some reasonable thickness of cover glass which would be effective in shielding the solar cells.

The Anna satellite 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, one will be better able to predict the effectiveness of the protection which can be gained by increasing the thickness of the solar cell cover slides.

Using solar cell data obtained from Transit 4B and TRAAC, one can predict the rate of degradation for certain satellite orbits. Fig. 7 shows the predicted performance as a function of time for several possible orbits. The curve for a satellite in the Transit 4B/TRAAC orbit (perigee = 960 km, apogee = 1106 km, inclination = 32°) predicts a 50% degradation in slightly more than 6 months. The predicted deterioration of solar cells for a polar orbiting satellite and for a satellite at lower altitude (for an inclination of 33°) is also shown. These two curves are based on comparing the particle flux levels calculated for various orbits with those predicted for the Transit 4B/TRAAC orbit† and then relating the solar cell damage to that suffered by Transit 4B satellite. It should be stated that the curves shown in Fig. 5 are still

† The calculations of radiation levels for various orbits were performed by W. N. Hess and his associates at the Goddard Space Flight Center using data obtained from the Injun I, Telstar, and TRAAC satellites.

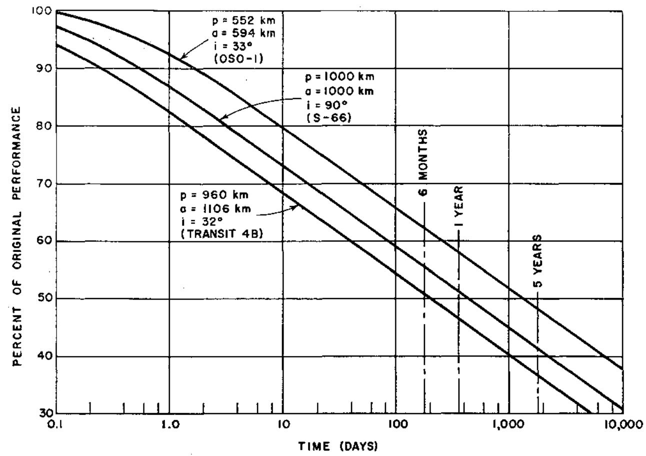


**Fig. 7 Solar cell performance as a function of time for several orbits**

preliminary. The time required to deteriorate to any particular percent of the original solar cell performance is prob ably accurate within a factor of 3. It should be stated further that these curves are for the short circuit current (at 0.2 v/cell) for *P*-on-*N*, "blue-sensitive" solar cells with a 6-mil cover glass. The use of thicker protection for the solar cells and especially the use of *N*-on-*P* solar cells or a combination of the two could have a significant effect in decreasing the rate of degradation.

Fig. 8 shows a preliminary concept of the artificial radiation belt as deduced by W. N. Hess from Ariel, Injun I,[7] Telstar, and TRAAC satellite data.[8] The radiation levels shown at altitudes greater than the 2 earth radii may be due in large part to natural Van Allen belt electrons rather than as a result of the nuclear test. However, whatever the cause of their presence, they appeared to be there in late July 1962.

### Conclusions

As a result of the high altitude nuclear explosion over Johnston Island on July 9, 1962, an intense electron radiation belt has been trapped in the earth's magnetic field. This artificial radiation 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. However, Anna satellite data from late in November 1962 have shown that the belt is down by a factor of approximately 3 since July 9 as far as the damaging effects of solar cells are concerned. Therefore, for late November 1962 the curves of Fig. 7 show approximately 3 times the expected rate of degradation. 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 power generating system of the satellite. 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 determined accurately until the energy spectrum of the trapped particles is better defined.

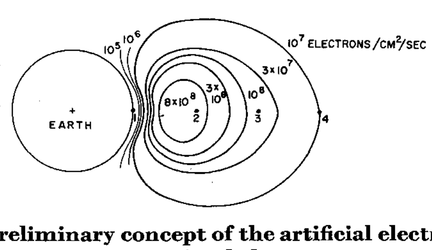


**Fig. 8 Preliminary concept of the artificial electron radiation belt**

### Acknowledgment

The author wishes to acknowledge the invaluable assistance of James W. Teener, of the Applied Physics Laboratory, for performing the numerous computations necessary to obtain the solar cell performance data presented herein.

### References

[1] Fischell, R. E., "Magnetic and gravity stabilization of earth satellites," *Space Research II, Proceedings of the Second International Space Science Symposium, Florence, Italy, April 10–14, 1961*, edited by H. C. Van DeHulst, C. De Jager, and A. F. Moore (North Holland Publishing Co., Amsterdam, Holland, 1961).

[2] Fischell, R. E., "Solar cell experiments on the Transit and TRAAC satellites," *Proceedings of Solar Working Group Conference, Feb. 27–28, 1962, Radiation Damage to Semiconductor Solar Devices, PIC-SOL 209/2* (Interagency Advanced Power Group, NASA, Washington, D. C., April 1962), Vol. I, pp. 6-2 to 6-27.

[3] Smits, F. M., Rosenzweig, W., and Brown, W. L., "Report of solar cell work at Bell Telephone Laboratories," *Proceedings of Solar Working Group Conference, Feb. 27–28, 1962, Radiation Damage to Semiconductor Solar Devices, PIC-SOL 209/2* (Interagency Advanced Power Group, NASA, Washington, D. C., April 1962), Vol. I, pp. 9-1 to 9-27.

[4] "Status report on trapped electrons from the Starfish high altitude test," joint report prepared by the Atomic Energy Commission, Dept. of Defense, and NASA (September 7, 1962), p. 7.

[5] Willmore, A. P., private communication (September 18, 1962).

[6] Carter, R. E., Reines, F., Wagner, J. J., and Wyman, M. E., "Free antineutrino absorption cross section," Phys. Rev. **113**, 283 (1959).

[7] O'Brien, B. J., Laughlin, C. D., and Van Allen, J. A., "Preliminary study of the geomagnetically-trapped radiation produced by a high-altitude nuclear explosion on July 9, 1962," Nature **195**, 939–943 (1962).

[8] "Status report on trapped electrons from the Starfish high altitude test," joint report prepared by the Atomic Energy Commission, Dept. of Defense, and NASA (September 7, 1962); also Hess, W. N. and Zakada, P., "Artificial radiation belt discussed in symposium at Goddard Space Center," Science **138** (October 5, 1962).

---

# Comments on "Re-Entry Trajectories: Flat Earth Approximation"

Everett W. Purcell*

*Aeronutronic Division, Ford Motor Company, Newport Beach, Calif.*

In a recent paper by Blum,[1] an excellent study is found on re-entry trajectory calculations. There is, however, a technical error in the first two equations which is propagated throughout the remainder of the paper. Although the result of this error is slight and does not invalidate the calculations given by Blum, it is an error commonly made by others and will now be discussed.

In deriving Blum's Eq. (1), one might obtain

$$d^2y/dt^2 = -g - (\rho A C_D/2m)V(dy/dt) \tag{1}$$

where $g$ is the gravitational acceleration that is, in general, a function of position, and where $m$ is the mass in gravitational units. Now, in order to introduce the ballistic parameter $\beta$ (a constant), which is defined by

$$\beta = C_D A/W \tag{2}$$

Received by ARS September 10, 1962.

* Research Scientist. Member ARS.

[1] Blum, R., "Re-entry trajectories: flat earth approximation," ARS J. **32**, 616–620 (1962).