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Comparison of DMSP and NTS-2 Dosimeter Measurements with Predictions

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The uncertainties in predicting the effects of energetic particles on satellite systems remain a concern to all spacecraft designers and users. Employing the latest models of the naturally trapped particle environment and current analytical techniques, a comparison of the measured and predicted space radiation dose for the Defense Meteorological Satellite Program (DMSP) and the Naval Research Laboratory (NTS-2) satellites has been made. These satellites are in different orbits and therefore encounter different environments; in both cases, the predicted doses differ somewhat from the measurements. Several reasons for these discrepancies are presented.

Introduction

THE Air Force Defense Meteorological Satellite Program (DMSP) has placed a spacecraft in a 450-n.mi. circular orbit with an inclination of approximately 96 deg (essentially polar). The Naval Research Laboratory has a Navigational Technology Satellite (NTS-2) in an 11,000-n.mi. circular orbit, inclined approximately 63 deg to the equator. Both of these vehicles have charged-particle dosimeters onboard and have been telemetering these data for extended periods. In this paper, a comparison of these measured doses with predicted doses is made using current analytical techniques.

The Space Particle Environment

In order to predict the dose from charged particles trapped in the Earth's magnetic field, it is necesary to have some knowledge of the expected flux and energy spectra of the electrons and protons incident on the spacecraft. For many years, the scientific community has relied on models of the trapped environment in making predictions of the radiation dose that an Earth-orbiting spacecraft is expected to receive. The latest versions of these models are identified as AE-6 and AEI-7 (inner and outer zone electrons)[1,2] and AP-8 (protons).[3] Because of the complexity and known variations in the trapped environment and limited input data with which to construct such models, these data are not believed to be accurate to better than a factor of 2 or more.

The DMSP satellite encounters both electrons and protons in the South Atlantic anomaly (inner zone) and electrons in the "horn" regions (outer zone). The NTS-2 spacecraft sees only outer zone electrons (see Fig. 1). [Low-energy ($\lesssim$4 MeV) protons are encountered, but, since they do not contribute to the measured doses, they are not considered in this paper.]

Figure 2 shows the predicted electron environment that the DMSP and NTS-2 are expected to encounter based on the AE-6 and AEI-7 models. The units are in electrons (per cm^2-day) with energy greater than E vs electron energy E, as applicable. This figure shows that the environment in the NTS-2 orbit is about a factor of 100 higher than the DMSP orbit. Figure 3 gives the predicted integral proton spectrum for the DMSP orbit as computed from the AP-8 model.

These environments have been used to make the dose predictions presented here.

Predicted Doses

Using these model environments together with a simplified (hemispherical shielding geometry, calculations of dose vs shield thickness have been made for the DMSP (F1) and NTS-2 satellites. These data are presented in Fig. 4 and are given in terms of rad/yr vs shield thickness in g/cm^2 of aluminum. The environments are assumed to be isotropically incident, and the per-day fluxes given in Figs. 2 and 3 are assumed to be constant over a one-year time period. These assumptions were made to facilitate comparison of the measured data.

The electron dose calculations were done using the TIGER code,[4] and the proton doses were taken from Ref. 5.

Spacecraft Dosimetry

The DMSP space radiation dosimeter consists of four separate cubical lithium-drifted silicon detectors measuring $1\times1\times1$ mm, covered by a hemispherical aluminum shell of 35, 75, 125, and 200 mils thickness, respectively, with heavy shielding over the solid angle of 2π sterad facing toward the interior of the spacecraft. Each detector, behind its respective shell, measures the total energy deposited in the depleted (active) volume by charged particles and gamma rays. The detectors are passively cooled to keep the system noise well below the electronic energy threshold set at 25 keV. A backup channel with a 75-keV threshold has been included in each of the four detector systems. A special gated integrating circuit associated with each of the eight detector channels monitors the deposited energy and produces output pulses, each of which corresponds to a dose of $\sim 8\times10^{-6}$ rad. The pulses are counted by scalers whose contents are read out by the spacecraft telemetry system. Maximum storage capacity of the scalers corresponds to an accumulated dose of 5.5×10^5 rad. The dosimeter was put into orbit aboard the first DMSP Block 5D Satellite (F35). This instrument is described in more detail in Ref. 6.

The NTS-2 satellite has two dosimeters designed to measure the radiation dose as a function of shield thickness. One of the dosimeters, built by the Naval Research Labortory (NRL), uses fiber optics as the radiation sensing element. The fibers darken when exposed to radiation, and consequently, the attenuation of light transmitted through the fiber becomes greater as the radiation dose increases. The second dosimeter measures the radiation dose directly in small silicon cubes. This sensor, built by TRW Systems,[7] was based on the design that is flying aboard the DMSP satellite. The NTS-2

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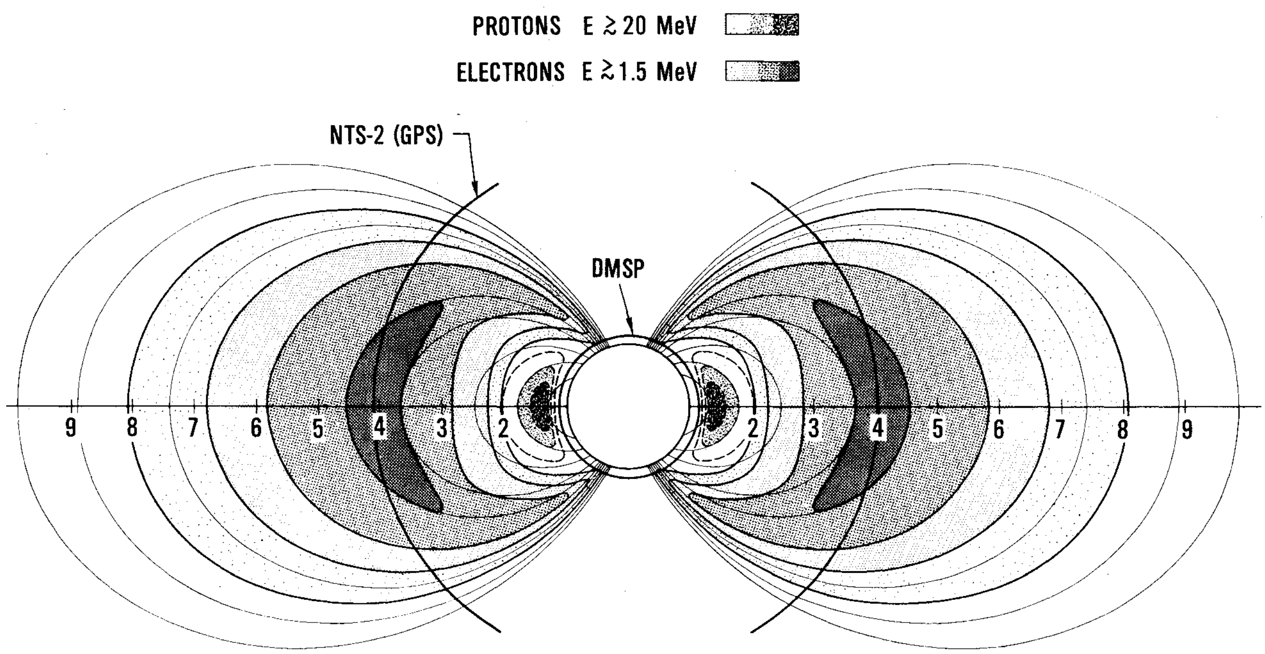

Fig. 1 DMSP and NTS-2 orbits relative to the geomagnetically trapped particle environment.

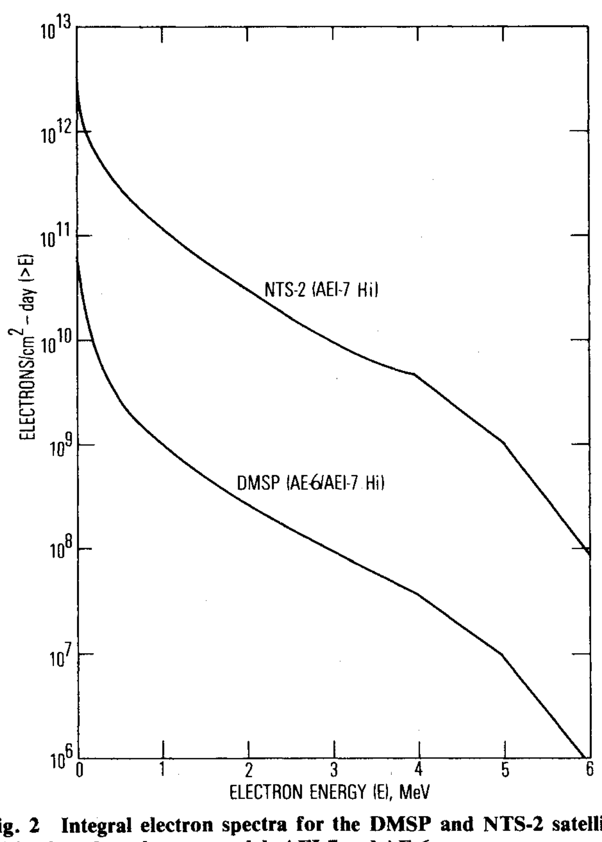

Fig. 2 Integral electron spectra for the DMSP and NTS-2 satellite orbits, based on electron models AEI-7 and AE-6.

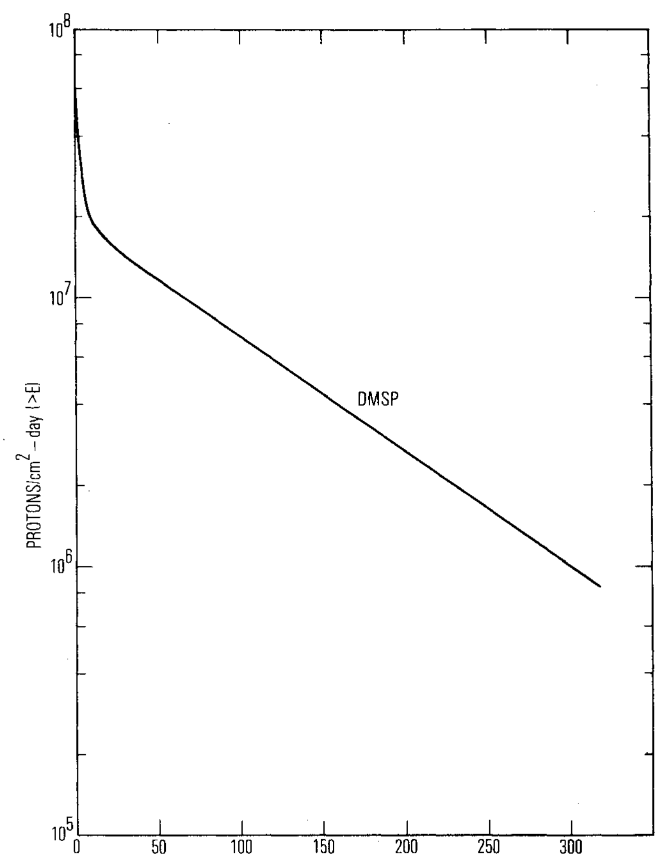

Fig. 3 Integral proton spectrum for the DMSP orbit, based on proton model AP-8.

dosimeters have three channels each with shielding thicknesses of 75, 250, and 400 mils of aluminum, respectively. Unfortunately, the NRL dosimeter was buried in the NTS-2 satellite in such a way that the actual shielding is complex, and thus, the response of the three channels is *not* a measure of the dose under the nominal shielding thickness. Furthermore, the glass contains a high-Z material, and thus, the depth-dose profile will not resemble that for silicon. The DMSP type dosimeter, however, was mounted with the hemispherical shields external to the satellite, giving a good 2π geometry. In this study, therefore, the main emphasis has been placed on the results of this dosimeter.

Measured Doses

Figure 5 gives the measured dose vs shield thickness for both the DMSP and NTS-2 satellites. The DMSP (F1) satellite was launched in 1976; because of technical difficulties with

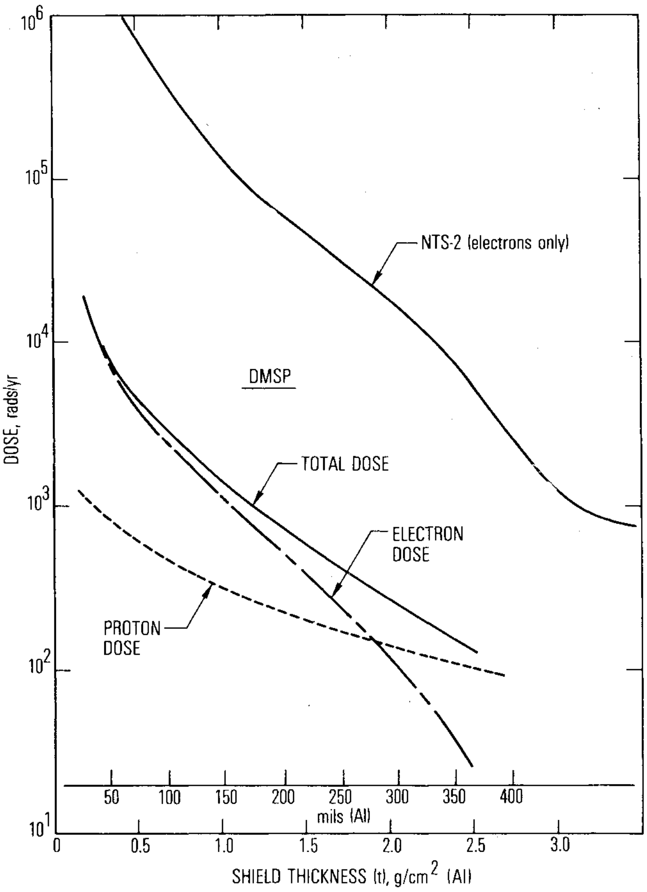

Fig. 4 Predicted dose in rad/yr vs shield thickness for NTS-2 and DMSP (2π geometry).

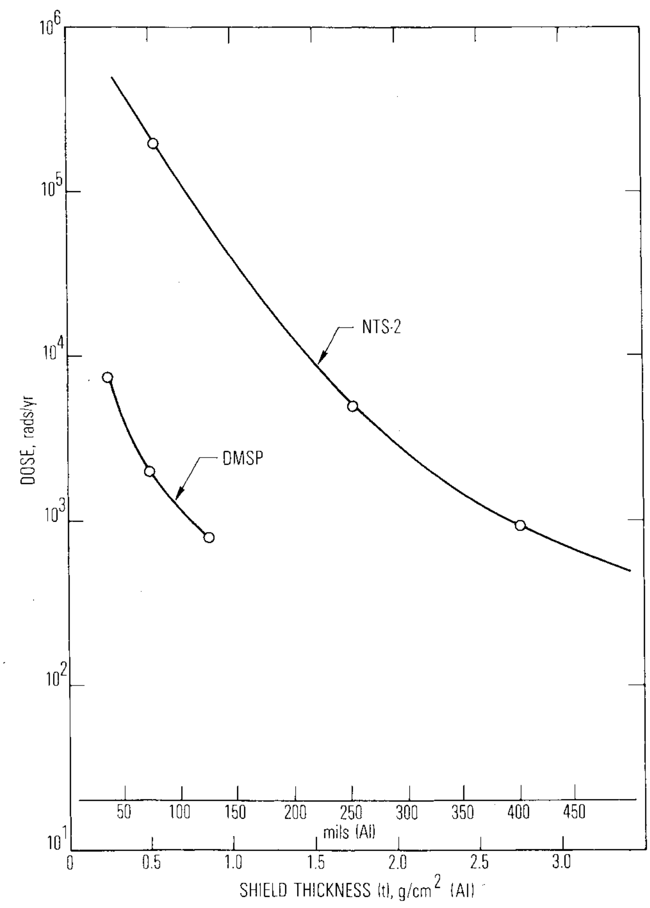

Fig. 5 Measured dose in rad/yr vs shield thickness for NTS-2 and DMSP.

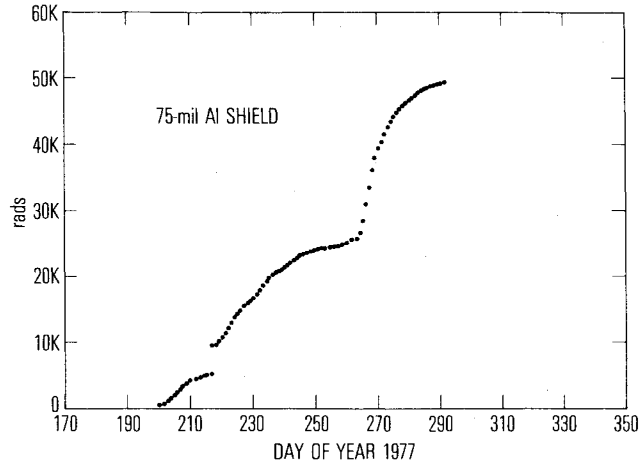

Fig. 6 Accumulated dose vs time for NTS-2, channel 1 dosimeter.

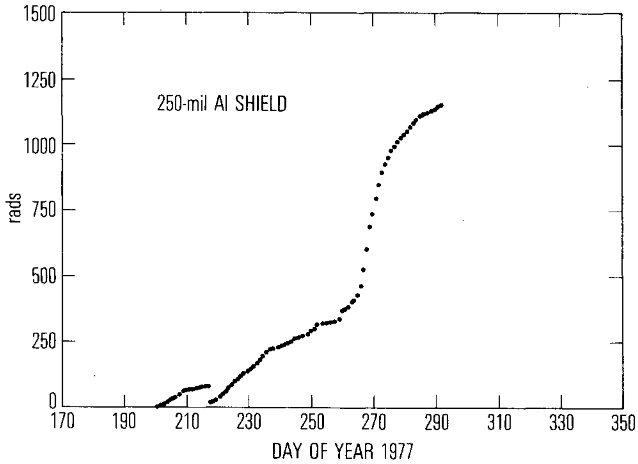

Fig. 7 Accumulated dose vs time for NTS-2, channel 2 dosimeter.

the satellite, dosimeter information was not available until April 8, 1977. The measured DMSP (F1) doses given in Fig. 5 cover the time period of April 8, 1977 through April 7, 1978 (one year). Because the detector amplifier system corresponding to the thickest shield (200 mils) is known to have suffered a gain degradation, it has not been included in the data set.

The NTS-2 satellite was launched on June 23, 1977, and the dosimeter was activated on July 17, 1977. The NTS-2 dose, plotted in Fig. 5, is the average dose for the July 17 to Oct. 31, 1977 time period (106 days) ratioed up to one year, i.e., (365/106) times the 106-day dose for each detector.

Figures 6-8 give the running history of the radiation dose as a function of time in the three channels. The effect of the geomagnetic storm in the Sept. 19-25, 1977 time period can be clearly seen. A discontinuity in the dose at day 217 can be seen in all three plots. The origin of this anomaly is not known for certain, but it appears as though a power transient partially scrambled the scalers. In any case, the anomaly has not reoccurred.

Comparison of Measured and Predicted Doses

Figure 9 is a plot of the predicted and measured total dose for DMSP taken from Figs. 4 and 5. Figure 10 gives the same data for the NTS-2 orbit. The predicted doses are higher than the measured doses for all shield thicknesses. This is true for both orbits.

Comparing the three valid data points (circles in Fig. 9) with the predictions for DMSP, it may be seen that the predictions are high by about a factor of 2. Since the dose for these shield thicknesses ($< \sim 1$ g/cm^2) comes primarily from

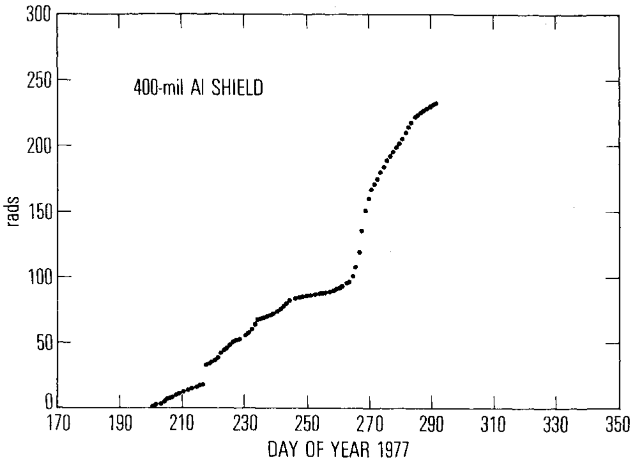

Fig. 8 Accumulated dose vs time for NTS-2, channel 3 dosimeter.

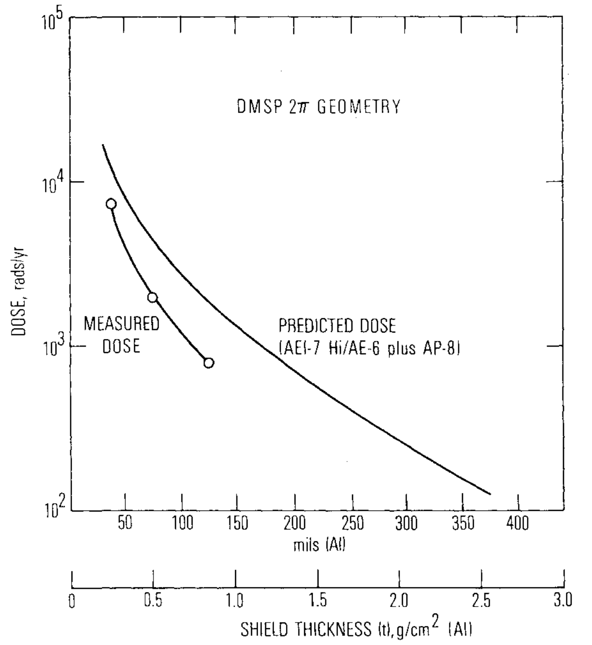

Fig. 9 Comparison of measured and predicted dose for DMSP orbit, 2π geometry.

electrons, this discrepancy might suggest that the AEI-7 Hi/AE-6 electron models are conservative (too high). However, when considering the fact that the time period (4/77-4/78) covered by these measurements was, by all standards, a relatively "quiet sun" time, then the comparison appears to be quite good. As the next solar maximum approaches, it is expected that the measured doses will more closely approximate the predictions since the AEI-7 Hi model is based on a level of geomagnetic storm activity that has not yet been seen.

In the case of NTS-2, the agreement is not quite so good as it is for DMSP. As seen from Fig. 10, the measured dose at the lowest and highest shield thicknesses (75 and 400 mils) is down by about a factor of 3 from the predicted dose. At the 250-mil data point, the measured dose is low by about a factor of 6. First, let us consider this factor of 6 in the shield thickness range around 2 g/cm^2. To do this it must be remembered that all the dose in the NTS-2 orbit comes from outer zone electrons (AEI-7), whereas the DMSP dose is composed of inner (AE-6) and outer zone (AEI-7) electrons plus protons (AP-8). Since the AEI-7 electron contribution to the DMSP total dose is not dominating, this enhancement at around 2 g/cm^2 is not present. For NTS-2, however, this

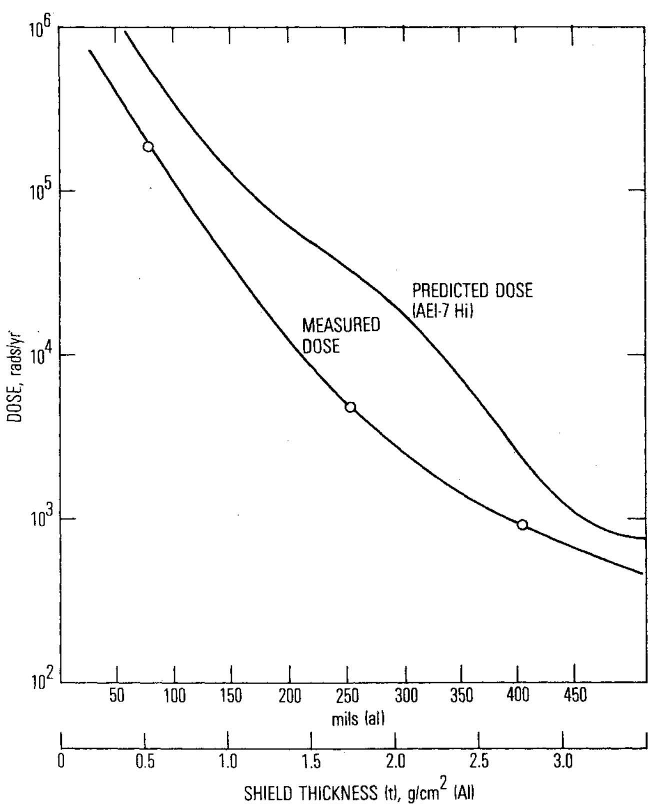

Fig. 10 Comparison of measured and predicted dose for NTS-2 orbit, 2π geometry.

phenomenon is very much in evidence; going back to Fig. 2, the reason for it can be seen. Notice that the AEI-7 electron spectrum forms a "cusp" at 4 MeV; since a 4-MeV electron is stopped by about 2 g/cm^2 of aluminum, we observe this "cusp" effect in the depth-dose curve at ~ 2 g/cm^2. The question is how realistic this peaking is in the AEI-7 electron model.

The AEI-7 electron model differs from the old AE-4 model[8] in two significant ways. First, it takes into account magnetic storm induced enhancements that have been observed to be factors of 30 higher than quiet times and for periods of several weeks, especially in the 3, 4, and 5-MeV range. Second, this enhancement of the higher energies produces a harder spectrum than AE-4. It is this difference that causes the "cusp" or peaking in both the NTS-2 integral spectrum and depth-dose curves.

A magnetic storm of some consequence was observed in the late August, early September 1978 time period, and it would be reasonable to expect this event to have produced an observable increase in dose for both DMSP and NTS-2. Since neither of these satellites was designed for quick response telemetry of the dosimeter data, it is not possible to present detailed information on their "storm time" response at this writing. It can, however, be categorically stated that the dose rates did increase for both satellites during this geomagnetically active period. Whether or not this or other magnetic storms will in time result in an electron environment and consequent depth-dose profiles that match the ones given by AEI-7 remains to be seen.

In summary, using present technology, it appears that the predicted doses for DMSP and NTS-2 orbits, using current models AEI-7, AE-6, and AP-8, are high by about a factor of 2. While this is a meaningful difference, it must be remembered that the models are not believed to be accurate to better than a factor of 2 or more. In addition, each storm-related increase in measured dose over the values given in Fig. 5 reduces this factor of 2 disagreement. In fact, it is not unreasonable to expect that, at the peak of the present solar cycle (1980-81), yearly dose rates in these orbits will closely approximate or perhaps exceed these predictions. In other words, there is agreement within the statistics of storm occurrences.

Conclusions and Recommendations

Based on the results of this study, the following conclusions and recommendations are offered.

1) The current proton model (AP-8) seems to predict the flux and spectrum of trapped protons for the DMSP orbit with a relatively high ($\pm 50\%$) degree of accuracy over the energy range from 12-38 MeV. (Protons of these energies are not encountered in the NTS-2 orbit.)

2) The electron model (AEI-7) predicts higher doses than those measured, but for a valid reason. AEI-7 takes into account the effects of magnetic storms that occur most frequently at solar maximum times, while the data taken from DMSP and NTS-2 represent relatively "quiet times." As solar maximum (~ 1981) approaches, the doses predicted using AEI-7 are expected to be in reasonably good agreement with actual doses.

3) Using simplified geometries (hemispherical) and allowing for the impact of the solar cycle, long-term (years) depth-dose calculations using AEI-7, AE-6, and AP-8 can be made that should be accurate to a factor of $\pm 50\%$.

4) Even though the AEI-7 electron model appears to predict higher doses than were expected (at least, during "quiet times"), it is at this time recommended that satellites continue to be designed to withstand this environment. It must be kept in mind that there are no assurances that the intensities and frequencies of the magnetic storms included in the AEI-7 electron model will not be exceeded during any given time period.

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