THE GEOMAGNETICALLY TRAPPED RADIATION ENVIRONMENT  
---A RADIOPHICAL POINT OF VIEW---  

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The regions of naturally occurring, geomagnetically trapped radiation (Van Allen Belts) are briefly reviewed in terms of physical parameters such as; particle types, fluxes, spectrums, and spatial distributions. The major emphasis is, however, placed upon a description of this environment in terms of the radiobiologically relevant parameters of absorbed dose and dose-rate and a discussion of the radiological implications in terms of the possible impact on space vehicle design and mission planning.

These descriptions are based both upon direct measurement and calculation using the more fundamental parameters of particulate energy and flux. Comparison of such calculations with measurements emphasizes that, depending upon the location in space, that calculational techniques are extremely dependent upon detailed knowledge of either the energy spectrum or material (shielding) distribution about the dose point -- or both.

INTRODUCTION

Since Van Allen's (ref. 1) discovery of areas of geomagnetically trapped radiation in 1958, there has been a tremendous amount of attention focused upon this phenomena. Upon only a cursory examination of launch records (refs. 2-5), it is easy to identify over a hundred satellites and several times that many non-orbital vehicles, during the 10 year period 1958-1968, which contained radiation measuring instrumentation. These experimental packages ranged from emulsions and simple/geriger systems, with which the discovery of the belts and the first identifications of electrons and protons were made (refs. 1, 6, 7), to extreme complexity. Some satellites carried several dozen different experiments. Many excellent reviews concerning the trapped radiation environment have been written (refs. 2, 8-16). White's (ref. 8) is perhaps the most succinct and easily read, while those interested in a rigorous treatment may consult Hess (ref. 2). Reference 16 is a compilation of all experimental data dealing with radiological parameters.

PHYSICAL PARAMETERS

Largely due to the efforts of Vette (refs. 17, 18), the results of a large number of satellite experiments have been combined to form a model of the geomagnetically trapped radiation zones. These environmental models are available in the form of synoptic maps of flux and energy spectrums (refs. 12, 16, 17, 18, 19, 20) and use the systematic coordinates B and L or R and L, which were developed by McIlwain (ref. 21). B is the magnetic field strength and L is a "magnetic shell" parameter relating the distance from the center of the earth through the magnetic equator to the point of interest. R is related to L through the expression \( R = L \cos^2 \Lambda \), and \( \Lambda \) is the angle to the geomagnetic equator. R and \( \Lambda \) are not the same as the geographic altitude and latitude and can be obtained only from the B-L system. For further discussions of these coordinate systems, the reader is referred to reference 21 and Chapter II of reference 16.

In general, the parameters which are of interest to designers and planners are those which will cause detectible influence on man or machine and these will be given the more thorough scrutiny by this writing.

Protons: There are distributions of high energy (10 to many hundred MeV) protons whose intensity varies with spatial location and has a maximum intensity at about \( L = 1.5 \) (L is expressed in units of earth radii). The intensity decreases to about \( 10^{-3} \) to \( 10^{-4} \) of maximum intensity at \( L = 3.0 \) with a smaller secondary maximum occurring at \( L = 2.2 \). At the position of the primary maximum, the integral flux above 34 MeV is approximately \( 2 \times 10^4 \) cm\(^{-2} \) sec\(^{-1} \). The spectral shape, although dependent upon spatial location, generally may be represented as decreasing exponentially, as shown in Figure 1 (ref. 16). Secondly, there are multilayers of low energy protons (0.1 to 10 MeV) surrounding the earth like "concentric skins on an onion" (ref. 8) with increasing energy toward the earth.
Electrons: There are two intense electron belts widely separated by a "slot" of considerably less and varying intensity. The "inner belt" maximum intensity occurs at $L = 1.4$ and has an integrated intensity above 0.5 MeV greater than $10^8 \text{cm}^{-2} \text{sec}^{-1}$ and consists of electrons with energies from a few keV to several MeV. This region is made up, primarily, of artificially injected electrons from the Starfish high-altitude nuclear explosion (1962) and does not fluctuate; however, the intensity decreases slowly with time as the electrons are lost into the atmosphere. The "outer belt", extending from $L = 3$ to $L = 6$, consists of natural electrons of lower energies and fluctuates with time. The integrated intensity above 0.5 MeV, at the maximum of this belt ($L = 4.5$ to $L = 5$), is in excess of $10^8 \text{cm}^{-2} \text{sec}^{-1}$. Although there were no extensive spectral measurements prior to the Starfish event, the inner belt electrons were identified in 1959, and the differential energy spectrum measured at $L = 1.3$, $B = 0.25$ (ref. 7). This spectrum decreased by a factor of 20 over the energy range from 100 to 450 keV and less than 3% of the measured electrons could have had energies in excess of 1 MeV. Cladis, et. al., (ref. 22) found that, in 1960, the outer belt could essentially be characterized exponentially with a 60 keV e-folding between 50 and 700 keV, a much steeper spectrum than the inner belt. These pre-Starfish spectrums may be compared with the 1962 (ref. 23) and 1966 (ref.24) spectral determinations shown in Figure 1, which include the Starfish electrons. Qualitatively, one may conjecture that the soft component shown is natural and that the harder component is the artificial contribution.

Heavy Ions: Krimmigs and Van Allen (ref.25), in 1967, first established the presence of heavy ions (helium nuclei) trapped in the geomagnetic field out to distances of 4 earth radii. The energy spectra are not unlike exponential functions and their intensity varies from 0.1 to 10% of the trapped proton component, depending upon spatial location. If, however, the intensities of both components are integrated above a common 0.5 MeV/nucleon energy, the helium to proton flux ratio is approximately $2 \times 10^{-4}$ at $L = 3.1$, $B = 0.19$.

A composite pictorial representation of the more penetrating components of the trapped environment is shown in Figure 2. The distributions of electrons with energies in excess of 0.5 MeV are displayed on the right side of the figure and proton distributions with energies exceeding 34 MeV are shown on the left. These distributions, of course, are contours of revolution around the earth and neither the many layers of low energy protons nor the heavy nucleii are represented.

RADIOLICAL PARAMETERS

The mission planner or spacecraft designer, who must determine potential material damage or biological hazards, is concerned with the energy that is deposited per unit volume at points of interest which are usually located within heterogeneous shield configurations. In such cases, an expression of absorbed dose at the point of interest is a highly useful parameter. This necessitates transport through surrounding shielding and calculation of energy deposition at a specific location. The trapped radiation environment with particle types, fluxes, and energy spectrums changing kaleidoscopically with spatial position (not to mention time) poses an extremely onerous task. This is further compounded, in the case of calculation of biological hazards, where the critical location may be influenced by spectral shape (i.e., a steep spectrum is more likely to reach an internal organ, with a low tolerance, than a soft spectrum). If the physical parameters are known in sufficient detail, these tasks may be accomplished with the aid of sophisticated computer programs; however, it is expensive and time consuming. In cases where the dose or dose-rate is needed only at selected points in space or the determination of only maximum levels is necessary, an environmental model expressed in terms of absorbed dose or dose-rate is the most practical tool. Such a model, including shield thickness as a parameter, obviates the necessity for lengthy computer calculations except where complex orbital parameters are involved or where extreme accuracy is required.

Contributions in this area have been made by the Biophysics Division of the Air Force Weapons Laboratory (ref. 16). Between July 1961 and May 1969, thirteen satellites and two sub-orbital probes were instrumented with combinations of instrumentation for the simultaneous measurement of both radiological and physical parameters. The dosimetric instrumentation consisted of tissue-equivalent ionization chambers, which responded with better than 90% accuracy (in mixed gamma, electron, and proton fields) from a few mr/hr to several hundred r/hr and advanced devices for the measurement of linear-energy-transfer (LET) in small volumes (refs. 16, 26, 27, 28, 29). These instruments were surrounded with varying amounts of either tissue-equivalent or elemental shields. The OV1-2 and OV3-4 satellites were typical of these vehicles and were designed for two specific purposes: (1) to provide a comprehensive synoptic dose-rate map of the trapped environment; (2) to provide a comprehensive synoptic dose-rate map of the trapped environment;
TRAPPED RADIATION ZONES

Figure 2. A model of the penetrating components of the trapped radiation environment, showing electrons on the right and protons on the left.
environment and (2) to study the effects of radiation spectra, anisotropy, and shielding heterogeneity on the calculation of electron, proton, and bremsstrahlung doses (refs. 16, 30, 31, 32). The instrument complements of these satellites is shown in Tables 1 and 2. In addition, further data was obtained by active and passive dosimetry systems flown in a number of Gemini and Apollo missions (refs. 16, 33, 34).

Dose-rate maps based on data from four of these satellites and the Gemini flights have recently been made available by reference 16. These are in either the B, L isodose format of Figure 3; the Dose-rate, B, Iso-L format of Figure 4; or geographic projections, of isodose contours at different altitudes. These are plotted in terms of dose rate beneath shielding material or in a more universally usable form of thickness of aluminum equivalent material. Table 3 gives a concise summary of the maps which are available in terms of B, L, dose-rate, and shielding thickness ranges. Data reduction efforts currently being performed will result in the production of comprehensive synoptic dose-rate maps covering the following ranges of parameters: (1) L = 1 - 5 earth radii, (2) B = 0.05-0.36 gauss, and (3) 0 - 16 gm/cm aluminum equivalent thickness of shielding material (ref. 35).

### Table 1

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Satellite</th>
<th>Type of Measurement</th>
<th>Dynamic Range</th>
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</thead>
<tbody>
<tr>
<td>Electron Spectrometer</td>
<td>OV1-2</td>
<td>Electron flux, energy 0.5 to 5.0 MeV in spectra, angular distribution</td>
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</tr>
<tr>
<td>Proton Spectrometer</td>
<td>OV1-2</td>
<td>Proton flux, energy spectra, angular distribution</td>
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<tr>
<td>Proton Spectrometer</td>
<td>OV1-2</td>
<td>Integral proton flux between limits, angular distribution</td>
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<tr>
<td>Osmidirectional Proton/Electron Spectrometers</td>
<td>OV1-2</td>
<td>Integral electron flux between limits, angular distribution</td>
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<tr>
<td></td>
<td>OV2-4</td>
<td>Proton flux, energy spectra, angular distribution</td>
<td></td>
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<tr>
<td></td>
<td>OV2-4</td>
<td>Electron flux, energy spectra, angular distribution</td>
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</tr>
<tr>
<td></td>
<td>OV2-4</td>
<td>Heavy Particle flux, energy spectra, angular distribution</td>
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### Table 2

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Satellite</th>
<th>Type of Measurement</th>
<th>Dynamic Range</th>
</tr>
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<tr>
<td>Proton Dosimeter</td>
<td>OV1-2</td>
<td>Energy deposition</td>
<td>0.5 to 4 x 10^4 MeV/sec (each detector)</td>
</tr>
<tr>
<td>X-ray/Bremsstrahlung Dosimeter</td>
<td>OV1-2</td>
<td>Energy deposition</td>
<td>1.6 x 10^4 to 5 x 10^5 MeV production in known shields</td>
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<tr>
<td>Tissue Equivalent Ionization chamber</td>
<td>OV3-1</td>
<td>Absorbed dose in rads/hr at depths of 0.6-2.9 and 8.0</td>
<td>10^2 to 10^3 rad/hr</td>
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<tr>
<td></td>
<td>OV3-1</td>
<td>Depth of 0.1-2.9</td>
<td>10^2 to 10^3 rad/hr</td>
</tr>
<tr>
<td></td>
<td>OV3-1</td>
<td>Depth of 0.1-2.9</td>
<td>10^2 to 10^3 rad/hr</td>
</tr>
<tr>
<td></td>
<td>OV3-1</td>
<td>Depth of 0.1-2.9</td>
<td>10^2 to 10^3 rad/hr</td>
</tr>
<tr>
<td></td>
<td>OV3-2</td>
<td>Linear energy transfer at depth of 2.5 in 10 log channels</td>
<td>5.0 g/cm^2</td>
</tr>
</tbody>
</table>

Figure 3. Typical Iso-L dose-rate profile map. The dose-rates are given in terms of amount (0.54 gm/cm^2) of aluminum equivalent material.
COMPARISON OF DOSE-RATE MEASUREMENTS WITH CALCULATIONS BASED ON PHYSICAL PARAMETERS

In those cases where extensive computer calculations using physical parameters must be performed, it is necessary to estimate the accuracy of the techniques. In order to better understand uncertainties in the transport calculations and the reliability of the available physical parameters, data from four satellites and two Gemini flights were extensively analyzed (refs. 12, 16, 19, 20, 31, 32). Data from three of the satellites included simultaneous measurements of both physical and radiological parameters and, thus, could be used to check both transport calculations per se, and dose calculations which were based on previously available data (refs. 12, 17, 18). It was determined that the available physical environment was inadequate, in many cases, to accurately predict the dose-rates which were encountered. The use of simultaneously measured flux, spectrums, etc. yielded much better agreement. These data were then used to "update" the available maps and, as a check, dose-rate calculations were performed for the remaining satellite and the two Gemini flights.

The results of calculations using both the old and new environments, shown in Figure 5 and Table 4, indicate that calculations based on the old (Vette) environment underestimated the dose-rate in heavily shielded detectors where high energy (E > 80 MeV) protons contribute heavily to the dose-rate.

It was also determined (refs. 16, 31, 32) that to correctly evaluate the results of lightly shielded detectors, which are either omnidirectional or do not provide "active collimation", a very sophisticated knowledge of the surrounding shielding (satellite and instrumentation) is necessary to adequately understand the data. This was also largely due to the much greater fluxes of high energy protons than had originally been estimated.

SUMMARY

Although nearly thirteen years has elapsed since the discovery of the trapped radiation environment and thousands of experiments performed, the data are insufficiently understood to accurately make estimates of radiological hazards.

Accurate calculations of doses have been possible only where precise determinations of the physical environment and spacecraft shielding were made. The only calculated results for a manned flight which were accurate to a factor of 2 were obtained using a simultaneously measured environment. In an unmanned craft on which a 1280 solid angle sectoring analysis of the shielding about the dose point was performed, the calculated and measured doses usually agreed to 50%. This latter used the new proton environment of contributions from protons with energies greater than 170 MeV.

**TABLE 3**

<table>
<thead>
<tr>
<th>Shielding (cm/cm² Al)</th>
<th>Range of E (MeV)</th>
<th>Range of L (Earth radii)</th>
<th>Dose-rate Range (rad/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.12-0.26</td>
<td>1.2 - 2.0</td>
<td>10⁻² - 10²</td>
</tr>
<tr>
<td>0.5</td>
<td>0.06-0.16</td>
<td>1.2 - 5.0</td>
<td>10⁻³ - 10²</td>
</tr>
<tr>
<td>1.0</td>
<td>0.06-0.26</td>
<td>1.2 - 1.5</td>
<td>10⁻⁴ - 10⁰</td>
</tr>
<tr>
<td>1.35</td>
<td>0.06-0.36</td>
<td>1.2 - 5.0</td>
<td>10⁻² - 50</td>
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<tr>
<td>1.40</td>
<td>0.12-0.28</td>
<td>1.2 - 2.0</td>
<td>10⁻² - 10²</td>
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<tr>
<td>1.50</td>
<td>0.16-0.30</td>
<td>1.2 - 2.0</td>
<td>10⁻⁴ - 10¹</td>
</tr>
<tr>
<td>2.6</td>
<td>0.06-0.10</td>
<td>1.0 - 2.6</td>
<td>10⁻² - 10¹</td>
</tr>
<tr>
<td>3.4</td>
<td>0.12-0.26</td>
<td>1.2 - 2.0</td>
<td>10⁻² - 10¹</td>
</tr>
<tr>
<td>4.0</td>
<td>0.06-0.23</td>
<td>1.2 - 2.0</td>
<td>10⁻² - 10¹</td>
</tr>
<tr>
<td>4.15</td>
<td>0.06-0.36</td>
<td>1.2 - 2.2</td>
<td>10⁻² - 10³</td>
</tr>
<tr>
<td>4.9</td>
<td>0.06-0.30</td>
<td>1.0 - 2.6</td>
<td>10⁻² - 10¹</td>
</tr>
<tr>
<td>16.0</td>
<td>0.12-0.26</td>
<td>1.2 - 3.7</td>
<td>10⁻² - 10³</td>
</tr>
</tbody>
</table>

Figure 4. Typical Isodose-Rate profile map. The dose-rates are given in terms of amount (0.54 gm/cm²) of aluminum equivalent material.
The data from both manned and unmanned spacecraft show that the largest uncertainty is consistently in the knowledge of the radiation environment. The inner trapped region ($L = 1$ to $2.0$) was divided into a high $B$ and a low $B$ region for comparison of calculation and measurement and very poor agreement was sometime found at the high magnetic field regions of the $L$ shells, regardless of the generation of the environment used. At low magnetic field regions of the $L$ shells, the Vette environment consistently underestimated the dose-rate by as much as a factor of 7; and the new environment, while better, yielded only a factor of 2 agreement in some regions.

The areas where manned flights occur are areas where the environmental data are most insufficient and the $B-L$ coordinate system tends to fail. There is clearly a need for further definitions of environmental parameters.

5. Iso-$L$ dose-rate profile map for a highly shielded dose point, showing correlation between actual measurements and calculations using both the Vette and Thede environmental models.
REFERENCES


35. Schneider, M. F., Private Communication.