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Solar Ultraviolet and Space Radiation Effects on Inflatable Materials

20 August 2000

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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13. ABSTRACT (*Maximum 200 words*)

Inflatable structures are being developed for use in space to take advantage of the potential for lower packaging volumes and lighter weights. These structures may consist of thin polymer membranes as well as more robust inflatable, then rigidizable, structural elements. For space applications, it must be shown that the materials can tolerate the orbital environment. This includes the effects of solar radiation and electron/proton radiation on the optical properties and mechanical response of the materials, as well as atomic oxygen effects for possible LEO applications. The highest radiation concern is with the thin-film materials, e.g., the canopy and reflector of an antenna or components of a sun shade or solar sail. All materials used in an inflatable structure need to be capable of tolerating the orbital environment and maintaining properties within the mission requirements.

The approach to assessing the effects of space environment on materials begins with consideration of the orbital environment. The solar radiation spectrum is not orbital dependent, but the radiation from electrons and protons varies by orders of magnitude, depending on the particular orbit. The atomic oxygen environment is strongly dependent on altitude and solar activity. Once an orbit has been defined, the atmospheric models are available to calculate the flux and energy of the particle radiation. The orbital lifetime then is used to calculate dose levels and solar exposures that the materials must tolerate. With the environment specified, the expected dose in the materials can then be calculated. If damage thresholds are available for the particular materials involved, possible degradation can be predicted; if not, a ground or orbital test is needed. For a ground test to assess the durability of a material in orbit, the methodology is to predict the dose levels in the materials, which then drive the test parameters.

The orbital environment of solar , electron and proton radiation are discussed. Typical levels for a LEO, MEO, and GEO orbit are presented, and examples of test conditions to simulate the space environment in a ground test on materials properties are discussed. Available results on materials for inflatables are presented.

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Preface

This work was prepared as a chapter for an AIAA Monograph titled: "Gossamer Spacecraft: Membrane/Inflatable Structures Technology".

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1. Introduction

Inflatable structures are being developed for use in space to take advantage of the potential for lower packaging volumes and lighter weights. These structures may consist of thin polymer membranes as well as more robust inflatable, then rigidizable, structural elements. For space applications, it must be shown that the materials can tolerate the orbital environment. This includes the effects of solar radiation and electron/proton radiation on the optical properties and mechanical response of the materials, atomic oxygen effects for possible LEO applications, and meteoroid and debris impacts. These latter two phenomena will not be discussed in this report. The highest radiation concern is with the thin-sheet materials, for example, the canopy and reflector of an antenna, or components of a sun shade or solar sail. All materials used in an inflatable structure need to be capable of tolerating the orbital environment and maintaining properties within the mission requirements.

The approach to assessing the effects of space environment on materials begins with consideration of the orbital environment. The solar radiation spectrum is generally not dependent upon orbital parameters (unless the orbit is significantly further from the sun than the Earth, such as an inter-planetary mission), but the radiation from electrons and protons varies by orders of magnitude, depending on the particular orbit and solar activity. Radiation levels for some typical spacecraft orbits are shown in Table 1. The atomic oxygen environment is strongly dependent upon altitude and solar activity. Once an orbit has been defined, atmospheric models are available that define the flux and energy spectrum of the particulate radiation.

With the environment specified, the expected radiation dose in the materials can then be calculated. If damage thresholds are available for the particular materials involved, possible degradation can be predicted. If not, a ground or orbital test is needed. For a ground test to assess the durability of a

Table 1. Typical Spacecraft Orbits

Spacecraft	Designation	Altitude, km	Type	Inclination (°)	Electrons/day/cm^2	Protons/day/cm^2
Various	Low Earth Orbit (LEO)	670	Circular	70	4.36 E10	7.11 E08
Defense Meteorological Satellite Program (DMSP)	Low Earth Orbit (LEO)	850	Circular	90	9.04 E10	1.58 E09
Various	Low Earth Orbit (LEO)	890	Circular	57	1.32 E11	5.11 E11
Various	High-elliptic orbit (HEO)	500-39660	Elliptical	60	3.50 E12	1.43 E12
Various	Middle Earth Orbit (MEO)	1600	Circular	60	2.02 E12	1.29 E13
Global Positioning Satellite (GPS)	1/2 GEO or GPS	20370	Circular	55	4.23 E12	3.90 E12
Defense Support Program (DSP)	Geosynchronous (GEO)	35670	Circular	0	4.94 E12	1.87 E12

material in orbit, the methodology is to use the prediction of the dose levels in the materials to drive the test parameters. The dose level in the material is defined as the amount of energy absorbed in the material. Common units of dose are the rad and the gray. A rad is defined as an absorbed energy of 100 erg per gram. A gray is defined as 1 joule per kilogram and is equal to 100 rads. A recommended test procedure is in preparation for space simulation testing that would apply to all materials, including inflatable materials.[1]

In this report, the orbital environments of solar, electron, and proton radiation are discussed. Typical levels for LEO, MEO, HEO, and GEO orbits are presented, and examples of test conditions to simulate the space environment in a ground test on material's properties are discussed. Available results on materials for inflatables are presented.

2. Space Environment Considerations for Materials Effects

The on-orbit solar spectrum includes the infrared (IR), visible, and ultraviolet (UV) regions, and extends into the vacuum ultraviolet (VUV) range. The VUV range is important because in this region there is sufficient energy to break chemical bonds in the exposed materials, resulting in possible decomposition. The on-orbit solar spectrum (ASTM Solar Air Mass Zero Curve) is shown in Figure 1.[2] The light sources used to reproduce this spectrum in laboratory tests will be discussed.

The space radiation environments of significance to the space inflatable materials community are geomagnetically trapped electrons and protons, and plasma/auroral electrons and protons. For most cases, contributions to the total dose from solar flare protons (and electrons) are negligible. The radiation levels vary widely depending on the intended orbit, so the orbital parameters are of prime importance in assessing the materials' performance for any application. The values in Table 1 represent an approximate daily fluence (electrons per cm^2) reaching a surface, but the energy (eV) of the incident particle defines the penetration. The information needed for a particular orbit is the flux (electrons/cm^2/s) of the radiation as a function of energy. That information is available from upper atmosphere models such as AE8 for trapped electrons,[3] AP8 for trapped protons,[3] and other models for plasma electrons and protons. One then calculates the fluence using the desired mission time.

For electrons, the AE8 MAX is used, while for protons, the model is AP8 MIN. The suffixes MAX and MIN refer to the relative solar activity (solar maximum or solar minimum) and are the worst-case

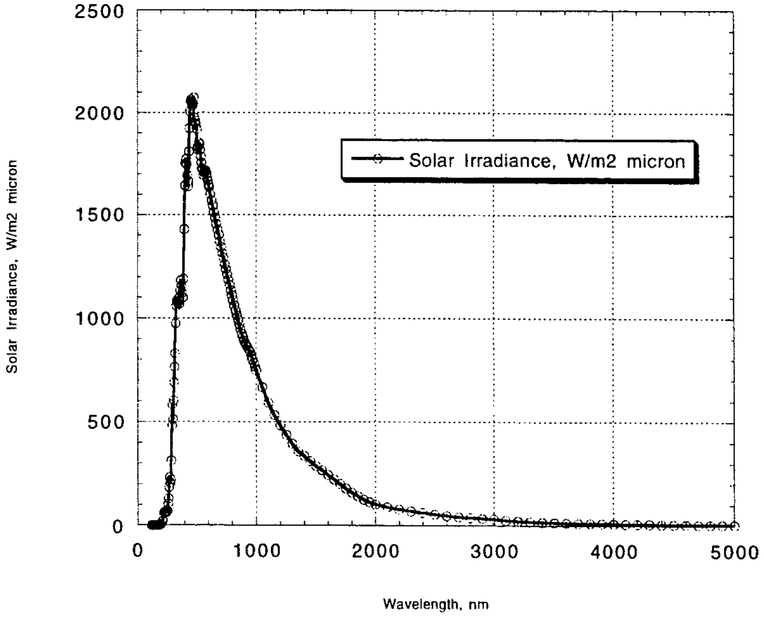

Figure 1. The air mass zero solar spectrum.[2]

conditions. These AE8/AP8 models effectively model the trapped or higher energy portion of the total charged particle environment. However, these models have been extrapolated from 40 keV to lower energies in the case of AE8, and from 100 keV in the case of AP8. This means that they are inaccurate and/or deficient at the lower particle energies. Separate models that specifically model this lower energy portion of the charged particle spectrum need to be incorporated into material dose calculations. This is important because, as inspection of Table 2 reveals, the flux of particles increases markedly with lower energies. Currently, there are no commonly agreed upon models for these low-energy/high-flux particles. Table 2 gives an example of an energy-flux table for a LEO orbit derived from the AE8 MAX trapped electron model.[3] The AE8/AP8 models are generally used for the calculations, but it should be realized that the actual dose generally must be higher than that calculated using only these models. The orbital lifetime determines the total dose that the materials must tolerate.

Table 2. AE8 MAX Model For LEO Orbit: 667 km (360 nmi)/70° Inclination.

Electron Energy, MeV E1 - E2,	**Electron Integral Flux > E1 Electrons/cm^2/day**	**Electron Flux, E1-E2 Electrons/cm^2/day**
0.00-0.04	4.36E+10	1.17E+10
0.04-0.07	3.20E+10	6.59E+09
0.07-0.1	2.54E+10	5.19E+09
0.1-0.2	2.02E+10	1.11E+10
0.2-0.3	9.08E+09	4.54E+09
0.3-0.4	4.54E+09	1.95E+09
0.4-0.5	2.60E+09	9.79E+08
0.5-0.6	1.62E+09	8.28E+08
0.75-1.0	7.88E+08	3.07E+08
1-1.25	4.81E+08	1.72E+08
1.25-1.5	3.09E+08	1.09E+08
1.5-1.75	2.00E+08	7.12E+07
1.75-2.0	1.28E+08	4.55E+07
2.0-2.5	8.28E+07	4.71E+07
2.5-3.0	3.57E+07	2.19E+07
3.0-3.5	1.38E+07	8.59E+06
3.5-4.0	5.20E+06	3.48E+06
4.0-4.5	1.71E+06	1.21E+06
4.5-5.0	4.98E+05	3.64E+05
5.0-6.0	1.34E+05	1.30E+05
6.0-7.0	3.72E+03	3.72E+03
7.0-8.0	0.00E+00	0.00E+00

3. Predictions of Radiation Levels in Thin-Sheet Membranes

Knowledge of the incident radiation levels as a function of energy and the orbital lifetimes enable the calculation of a dose-depth curve for the exposed materials. A computer code that employs a Monte Carlo routine is generally used for this calculation, and sufficient trajectories are used to produce a smooth curve. Two separate calculations must be run to obtain separate electron and proton dose-depth curves. Examples are shown in Figures 2a and 2b for electrons and protons, respectively. Figures 2a and 2b through 5a and 5b provide examples of the orbital doses in Kapton using AE8 MAX for electrons, and AP8 MIN for protons, for selected cases of the various orbital types: LEO, MEO, HEO, and GEO. In these, and all following graphs, mils (1.0 mil = 25.4 μm = 2.54 E-05 m) is the unit used for thickness.

Calculations of the dose profiles are clearly dependent upon the environmental models that generate the inputs for the radiation transport codes. The AE8 model is the standard model used for predictions of on-orbit radiation. However, the surface dose of materials is strongly dependent on the low-energy particles for both electrons and protons, but AE8/AP8 do not correctly model the low-energy plasma radiation. Figure 6 presents electron dose calculations for a GEO orbit using the standard

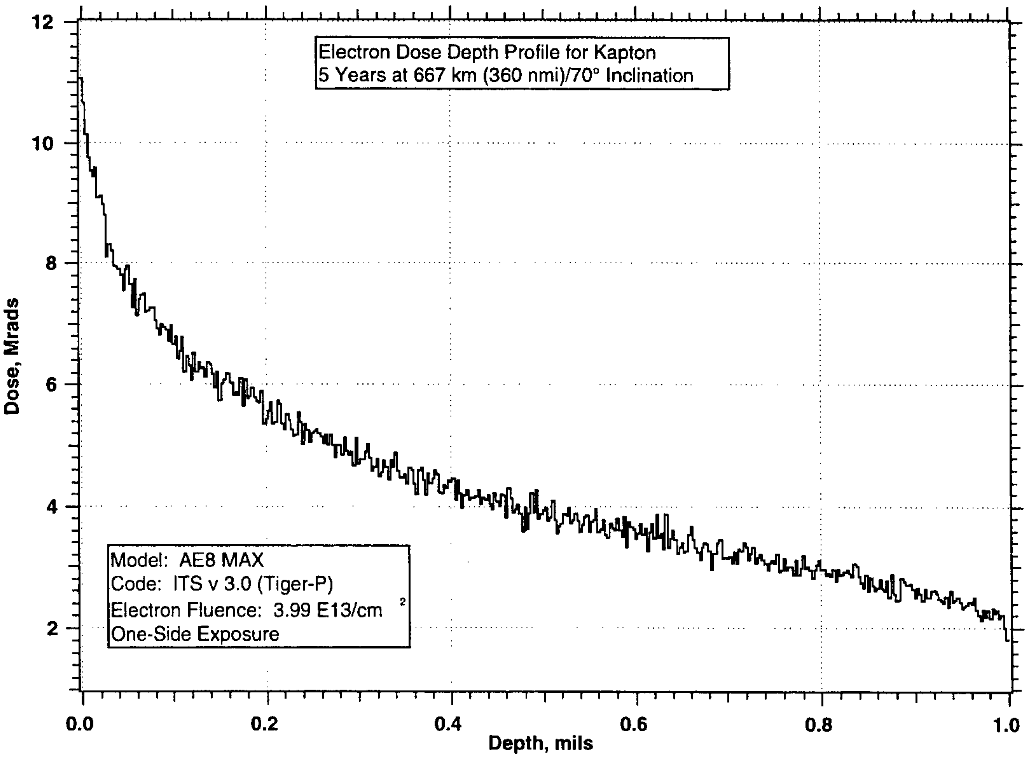

Figure 2a. Predicted electron orbital dose profile for a LEO orbit.

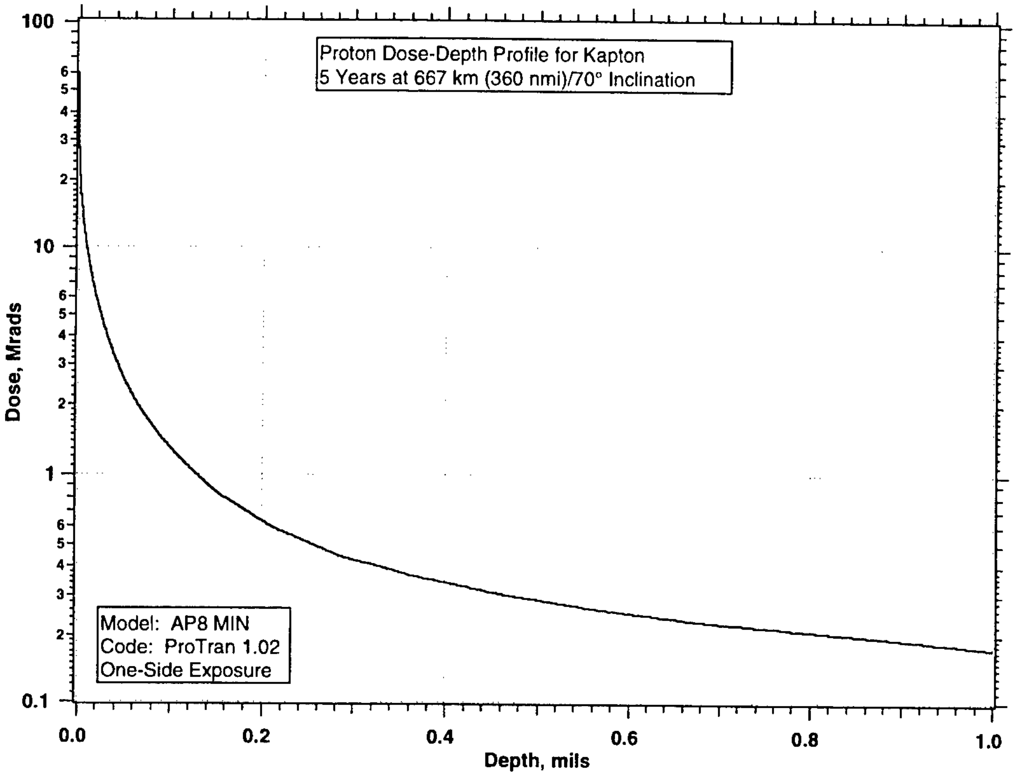

Figure 2b. Predicted proton orbital dose profile for a LEO orbit.

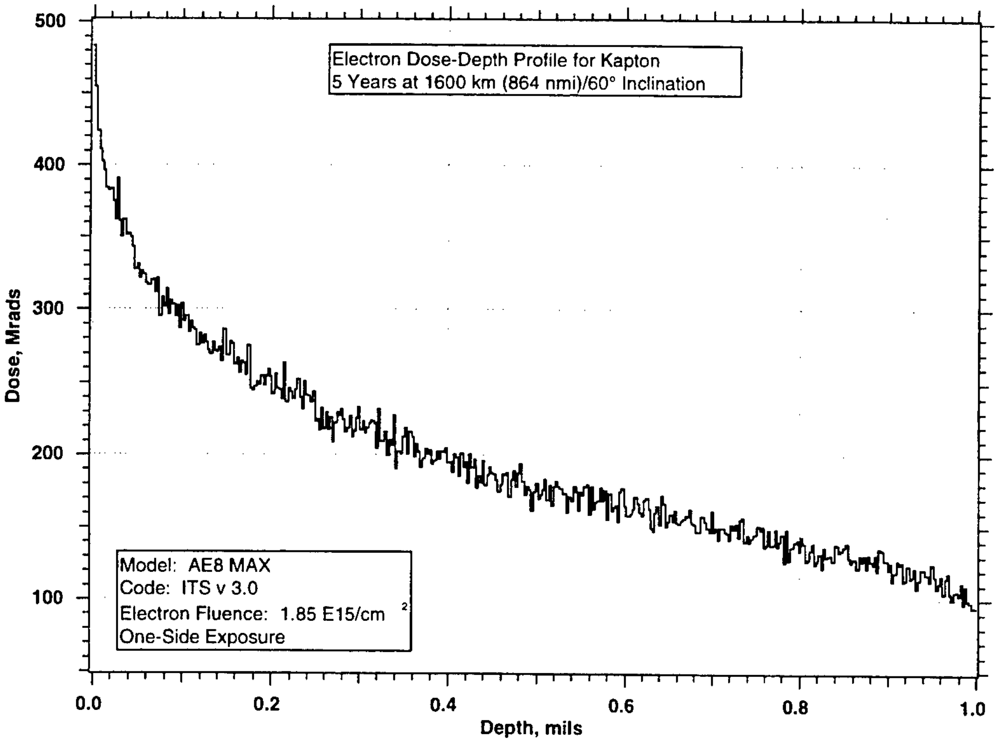

Figure 3a. Predicted electron orbital dose profile for a MEO orbit.

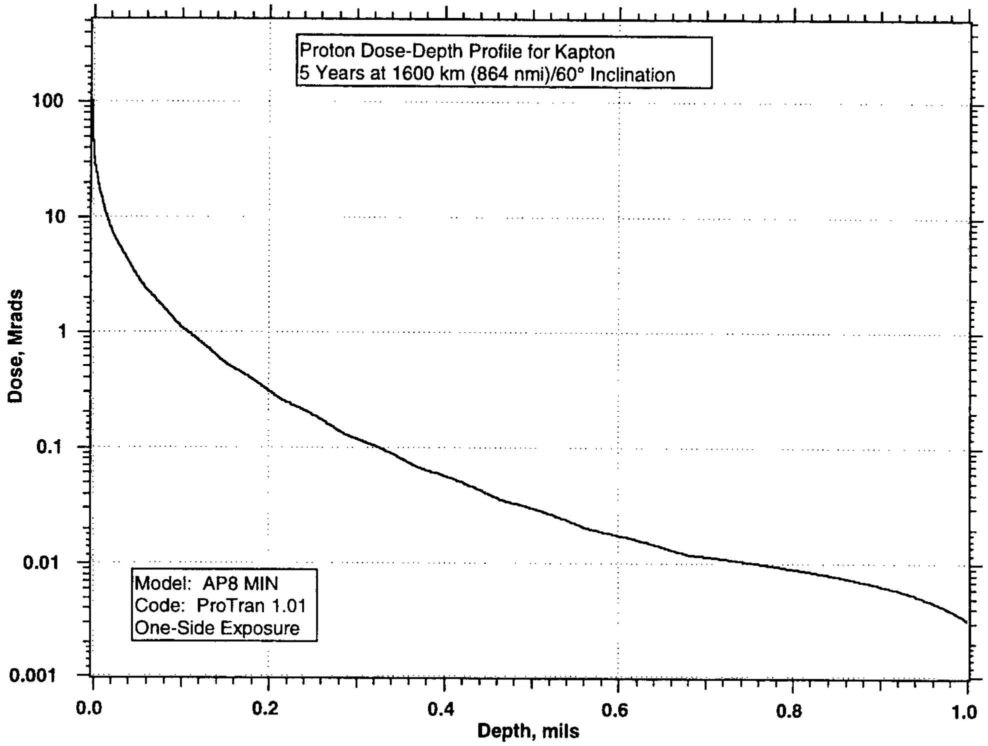

Figure 3b. Predicted proton orbital dose profile for a MEO orbit.

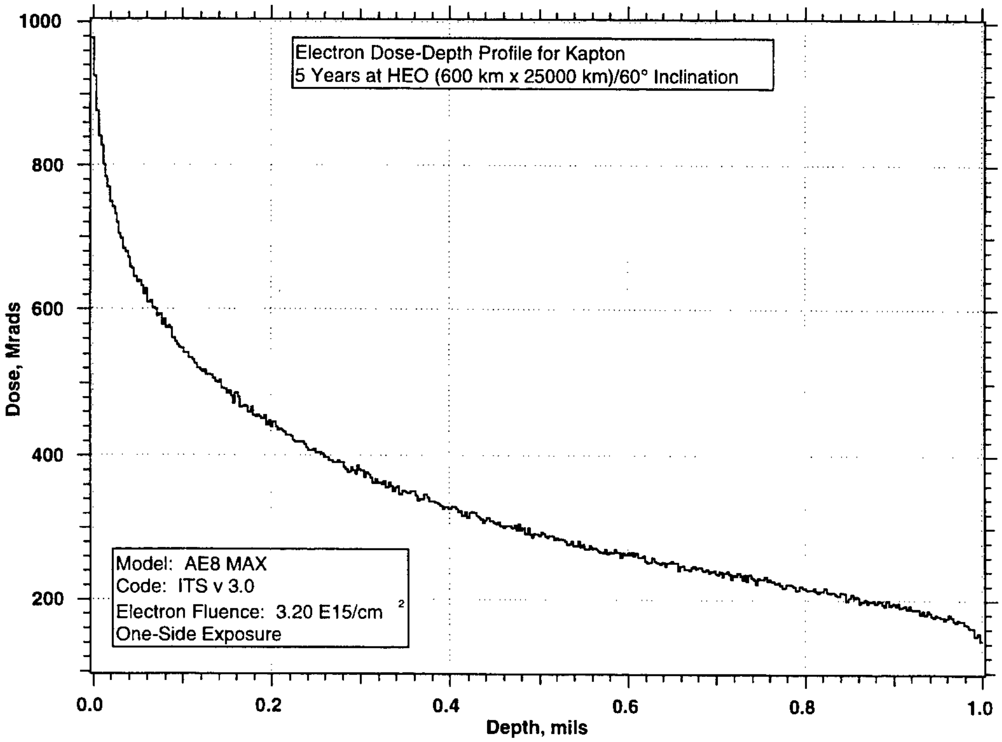

Figure 4a. Predicted electron orbital dose profile for a HEO orbit.

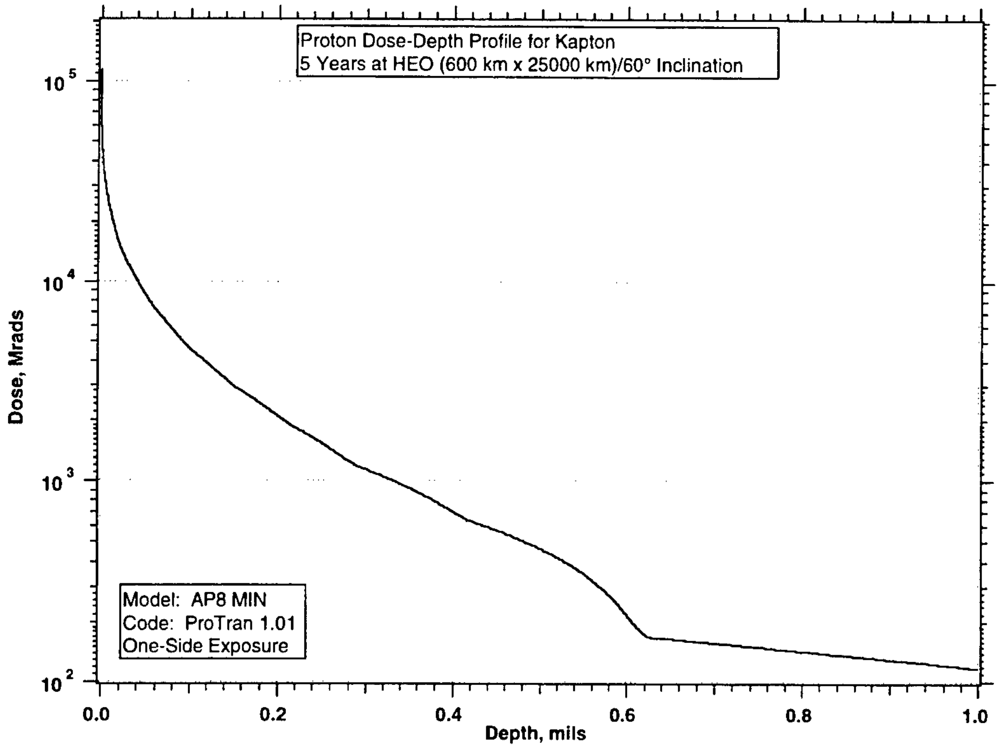

Figure 4b. Predicted proton orbital dose profile for a HEO orbit.

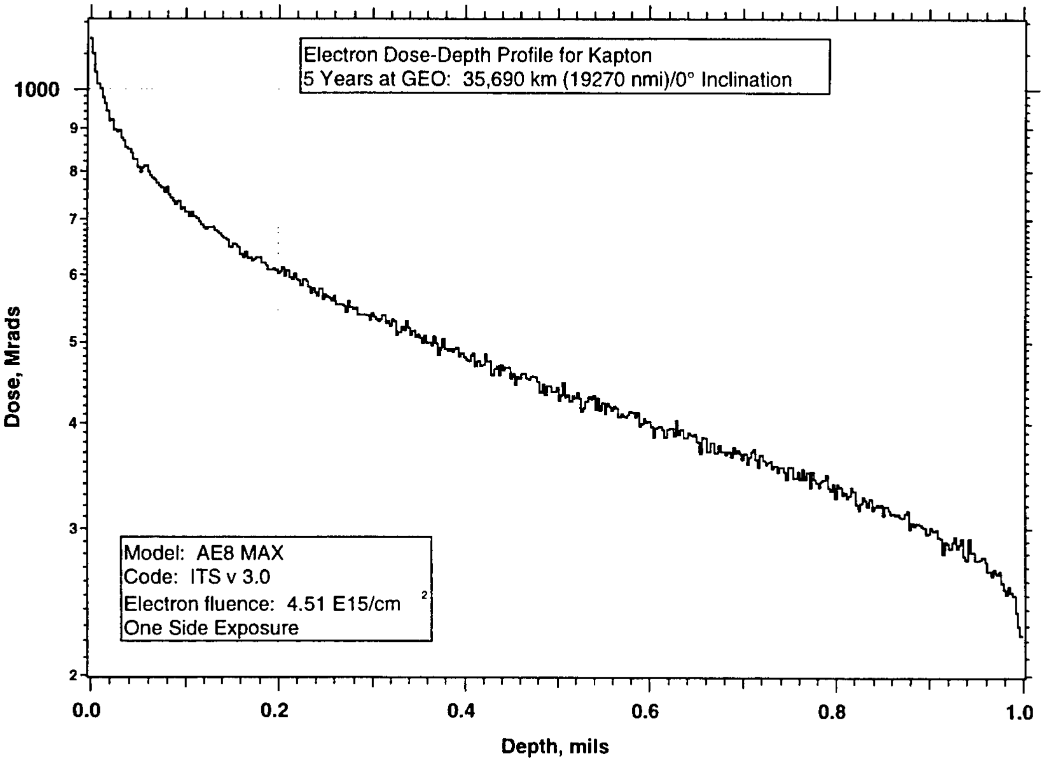

Figure 5a. Predicted electron orbital dose profile for a GEO orbit.

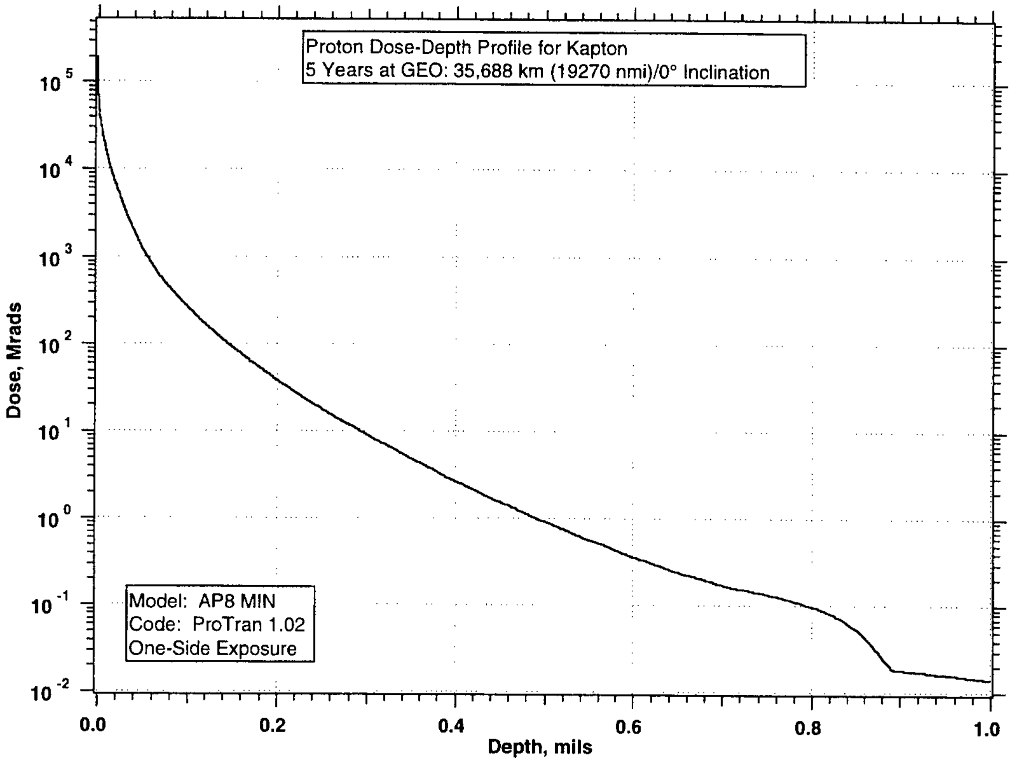

Figure 5b. Predicted proton orbital dose profile for a GEO orbit.

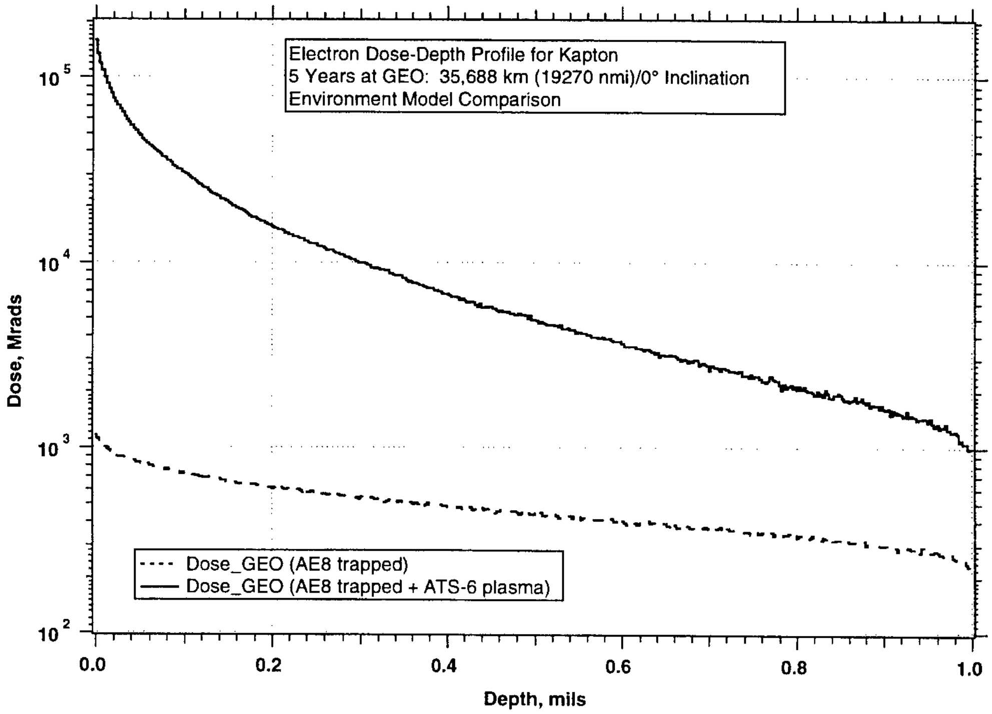

Figure 6. Comparison of orbital dose profiles for GEO orbit using Trapped and Plasma Models.

AE8 MAX model only, and also adding in the plasma environment model ATS-6.[4] It can easily be seen that the contribution from the lower energy plasma model overwhelmingly drives the material's surface dose. This is due to the very high fluences of low-energy plasma electrons relative to the higher energy trapped electrons in the AE8 model.

Two conclusions become apparent from this example: (1) Modeling the dose in thin materials without the inclusion of low-energy plasma electrons will lead to erroneously low calculated fluences, and (2) errors in the plasma models will greatly affect the calculated dose in thin materials. For all but the GEO case presented here, the low-energy plasma electrons (and protons) have not been included. This is the result of inadequacies in the plasma/auroral models for these orbits. For the HEO case, one could use the GEO plasma model and scale it to the time that the spacecraft remains at apogee. For the LEO case, there are newer models becoming available that model the auroral component of the low-energy electron environment.[5] For the LEO case, the contributions from the low-energy plasma may not be as large relative to the GEO/HEO cases. The MEO case remains a place where more work on plasma electron models needs to be done.

For these thin materials, double-sided calculations that take into account exposure from both sides become important, especially for electrons, which have much deeper penetration into materials. Electrons deposit their energy over a longer range, relative to protons, which primarily deposit their energy at the surface. The Figures 5a, 5b, and 6 illustrate this. For this GEO case, it can been seen that the dose due to protons drops 7 orders of magnitude over a thickness of 25.4 μm (1.0 mil). For the electron radiation, the corresponding change is only 1–2 orders of magnitude.

For a 25.4 μm (1.0 mil) outer layer of a multilayer insulation (MLI) blanket, the exposure can be modeled as a one-sided exposure since the extra layers beneath the top layer (and the structure beneath the blanket) absorb and shield the rear surface of this top layer. However, in an inflatable antenna that has a 25.4 μm (1.0 mil) or less canopy and rear reflector, the exposure then becomes significant on the internal faces of the membranes since the shielding is only from the opposite thin face. Figures 7 and 8 indicate this effect, which present electron dose calculations for a 25.4 μm (1.0 mil) Kapton sheet assumed to be shielded on the rear face, such as on a MLI blanket. For comparison, the dose is shown for a 25.4 μm (1.0 mil) inflatable sandwich composed of two 12.7 μm (0.5 mil) layers. The surface dose, and more importantly, the deep dose, in the two sides is significantly higher than a one-sided exposure calculation would indicate. However, while the relative magnitude of the dose is different in these two examples, both dose-depth curves are still strongly exponential and require that several energies be used to adequately simulate this profile in the laboratory. Very thin optical or metallic coatings of 1.0 μm or less, on the two faces would be second-order considerations in modeling the dose profiles. Proton double-sided calculations are not warranted since the dose drops by such a large amount through the material relative to the electron dose, as discussed previously.

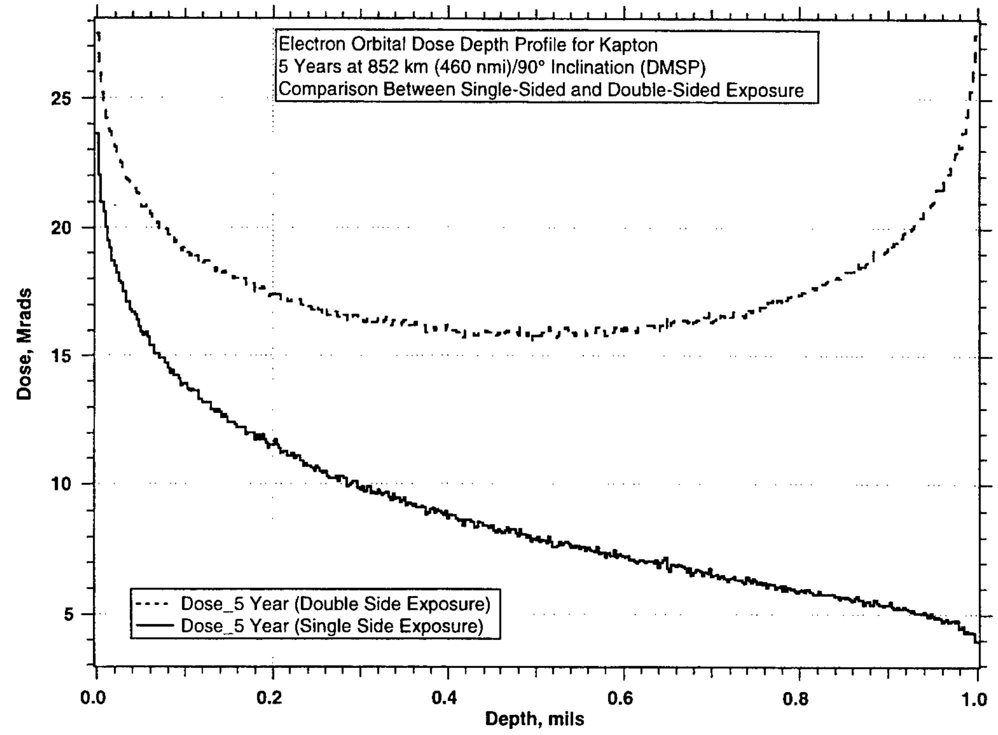

Figure 7. Comparison of single vs. double sided orbital dose profiles for 852 km (460 nmi)/90° LEO orbit

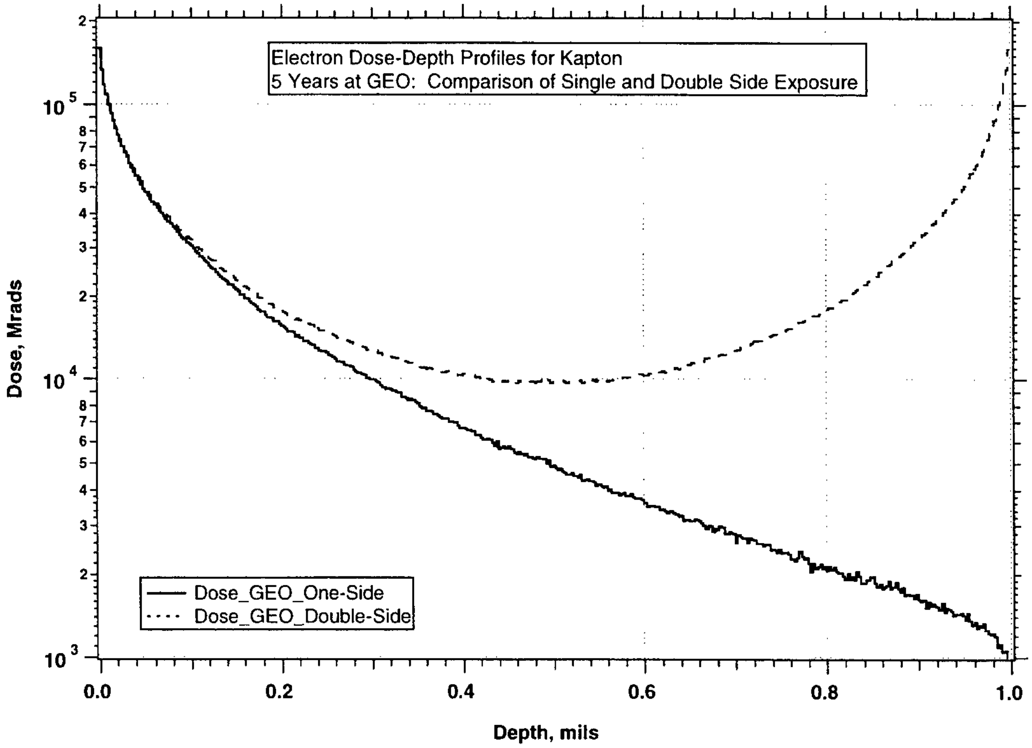

Figure 8. Comparison of single and double-sided orbital dose profiles for GEO orbit.

4. Thin-Sheet Material Results

Once the radiation dose levels are known, the potential for damage to the materials can be assessed. Some general comparisons of the relative stability of various materials are shown in Figure 9.[6] More specific for inflatable structures, there have been two recent experiments to study property changes in

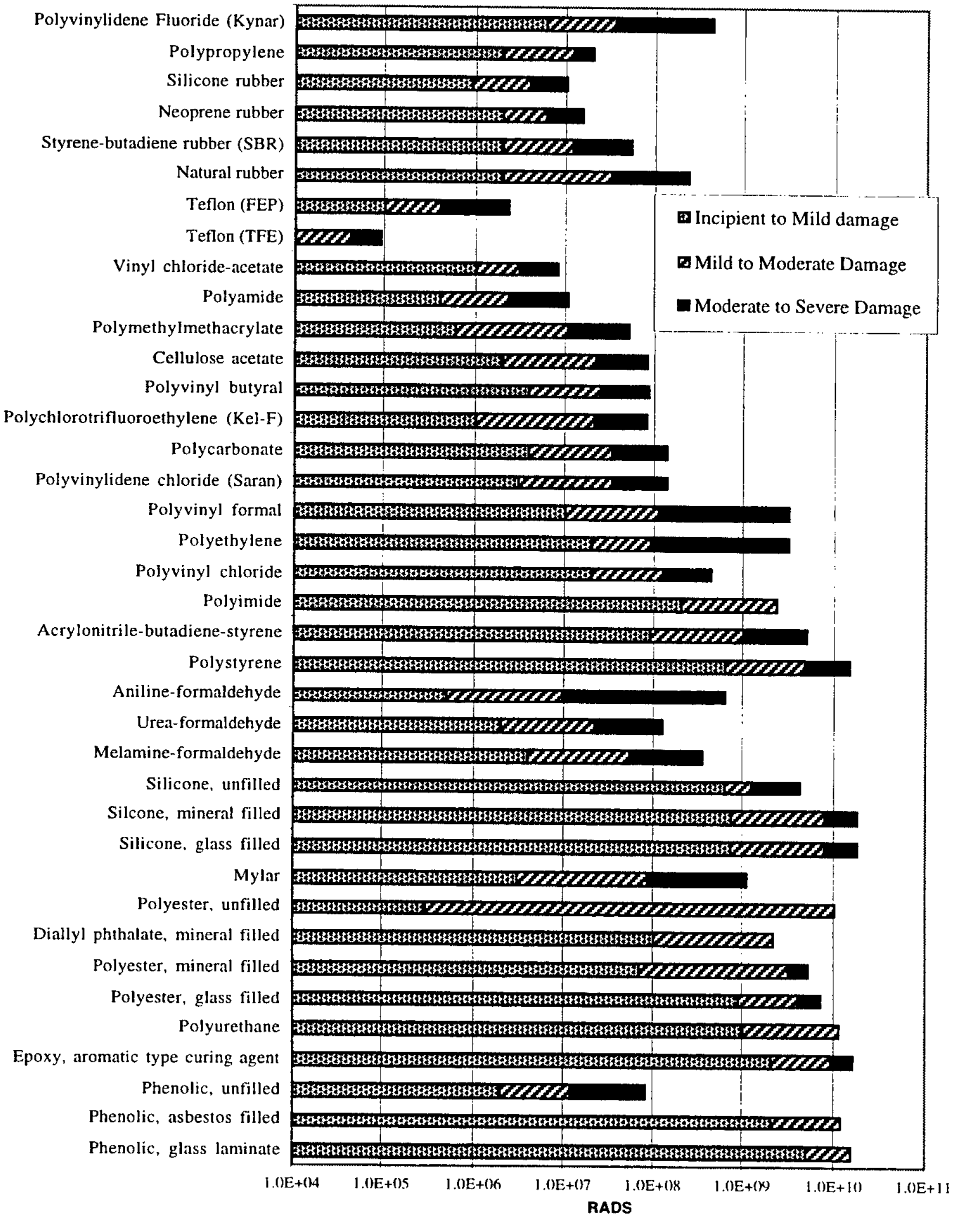

Figure 9. Relative Radiation Resistance of Some Polymeric Materials.[6]

thin polymer films in the space environment. Polymers included in both tests consisted of polyimides Kapton E, CP-1, and CP-2. Other materials such as Kapton HN, TOR, TOR-LM, TOR-RC, COR, and Upilex were also included, but not all of them in both tests. One test was for a five-year simulation of a LEO environment and a five-year GEO environment.[7] Test conditions were selected, as discussed later, with 10, 20, and 40 keV electrons sufficient for the 12.7 μm (0.5 mil) sheets. The solar UV radiation was 3200 equivalent sun-hours (ESH) for the LEO exposure and 4400 ESH for the GEO exposure, from a combination of a xenon arc lamp for long wavelength UV (230–400 nm) and a deuterium arc lamp for vacuum ultraviolet (VUV) radiation (115–200 nm). The other test was for a 5-year simulation of the environment corresponding to the Lagrangian point L1 at 0.98 astronomical units, with the major environment contributions similar to that of the second Lagrangian point L2.[8] This test included 40 keV protons, 40 keV electrons, and a total of 1000 h of UV exposure from a xenon arc lamp. Solar absorptance and mechanical property measurements were performed in both experiments and are included in the References 7 and 8. All samples in the exo-atmospheric test were metallized. The Kapton E, CP-1 and CP-2 samples in the LEO and GEO tests were not metallized.

Solar absorptance measurements were made of all samples in each test by measurement of the reflectance. Because of the differences in metal coatings for each set of samples, the results cannot be compared directly, but general comments follow. (Refer to References 7 and 8 for specific details.) The measurements for the LEO and GEO exposures were made immediately after removal from the test chamber. The measurements for the exo-atmospheric exposures were made in-situ. The Kapton E showed little change in solar absorptance in the LEO and GEO test, while the CP-1 and CP-2 samples showed small increases in solar absorptance. For the exo-atmospheric test, the Kapton E showed about a 25% increase, and the CP-1 and CP-2 approximately doubled. In general, greater increases in solar absorptance were observed for the exo-atmospheric simulation that had a higher electron fluence and included protons, which are strongly absorbed in the outer 2.5 μm (0.1 mils) of the polymer sheets.

Mechanical properties were measured in both space simulation experiments on thin-sheet materials. However, the number of samples is small, and statistically significant property data has not been obtained. There are trends that are consistent between both experiments that indicate the mechanical property changes that might be expected. The tensile modulus for thin polymer sheets does tend to decrease. A change in mechanical response would have to be compensated in the design to maintain a stable inflatable structure. A decrease in the failure stress and the strain to failure was observed in both tests. The failure strain has been observed to be as low as a few percent. Most inflatable structures have low film stress, but the increased susceptibility for failure with lower stress and strains needs to be carefully assessed for long-lifetime missions.

5. Simulation of Space Environment Effects

When data is not available, a space simulation test may be performed to obtain data on the acceptability of a material for a particular application and orbit. It is impossible to reproduce exactly the space environment for ground testing of space system elements because of the variety and complexity of the environments and effects on materials. The reliability of the test results depends on simulating the critical effects of the space environments for a particular mission.[1] A test must involve consideration of both the solar UV and particulate radiation.

An inflatable structure used on an Earth-orbiting satellite may, or may not, be continuously in full sun. About 5000 ESH is typical for a spacecraft surface exposure for a 5-year LEO mission, with degradation generally being greatest in the early exposure times. Material property changes from solar radiation normally have stabilized with a 5000 ESH. The solar spectrum is simulated using a xenon arc lamp that produces UV radiation over a 200–400 nm range along with white light with a distribution similar to the solar spectrum. The VUV range must be supplied with other types of lamps. A deuterium arc lamp is one option and is used in The Aerospace Corporation simulations. Other options are krypton and xenon resonant gas lamps.

The electrons (and, if included, protons) are added in the presence of solar UV using fixed energies and fluences from the electron gun on the simulation chamber. The electron fluences are based on the previously discussed prediction of the electron depth-dose profile in Kapton for the assumed orbit using AE8 and plasma model predictions of electron fluences. To decide on the energies that should be used to simulate the on-orbit dose profiles, it is illustrative to look at the energy deposition profiles of various monoenergetic electrons of increasing energy, together with the energy deposition profile for the orbit of interest. This is shown in Figure 10 for Kapton using the GEO energy profile.

The best match of the depth-dose profile is selected using a linear combination of multiple electron gun energies. It can easily be seen from Figure 11 that several energies are required to match the orbital profile through the entire thickness of the material. Test conditions that use only one energy, such as 1 MeV electrons, clearly cannot duplicate the correct profile through the material. For this reason, testing with a Van De Graf accelerator (Dynamitron) or a Cobalt-60 gamma radiation source (which produces scattered electrons of roughly 1 MeV), both of which provide electrons in the 1 MeV range, is generally inappropriate. Similarly, testing with very low energy electron beams, such as 1–10 keV alone, is inadequate to duplicate the dose profile through the material. An exception to these remarks would be a test using 1 MeV electrons applied to give the correct calculated surface dose level in a material and thereby overtesting the rest of the material. If the material passes this significant overtest, it may be considered qualified. This methodology works fine for low doses such as found in LEO or some MEO applications, but must be used with caution for HEO, GEO, or other high dose level applications.

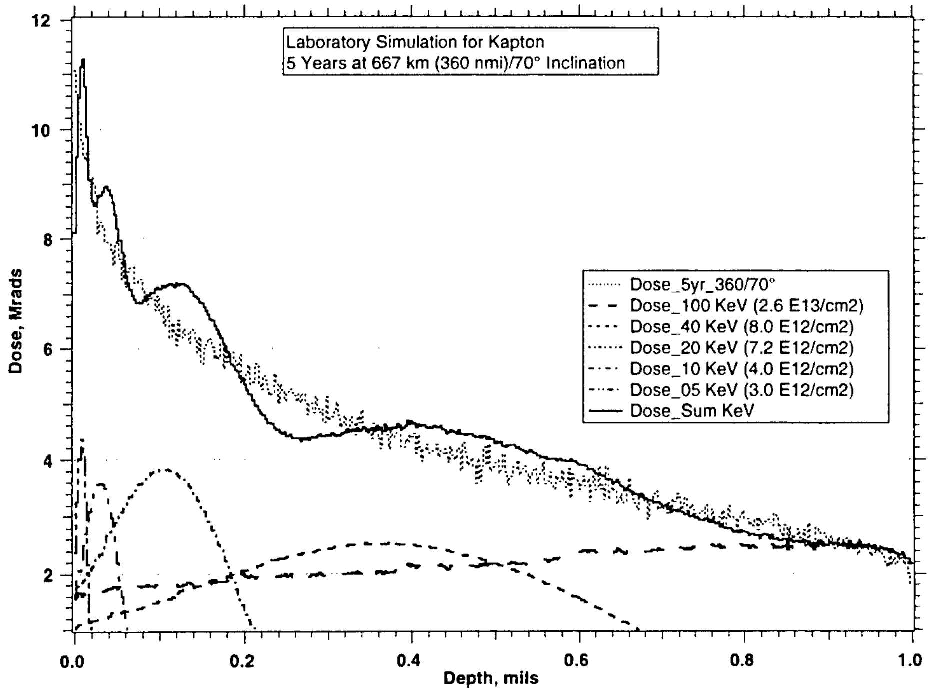

Figure 10. Predicted simulation dose profiles and orbital dose profile for 667 km (360 nmi)/70° LEO orbit.

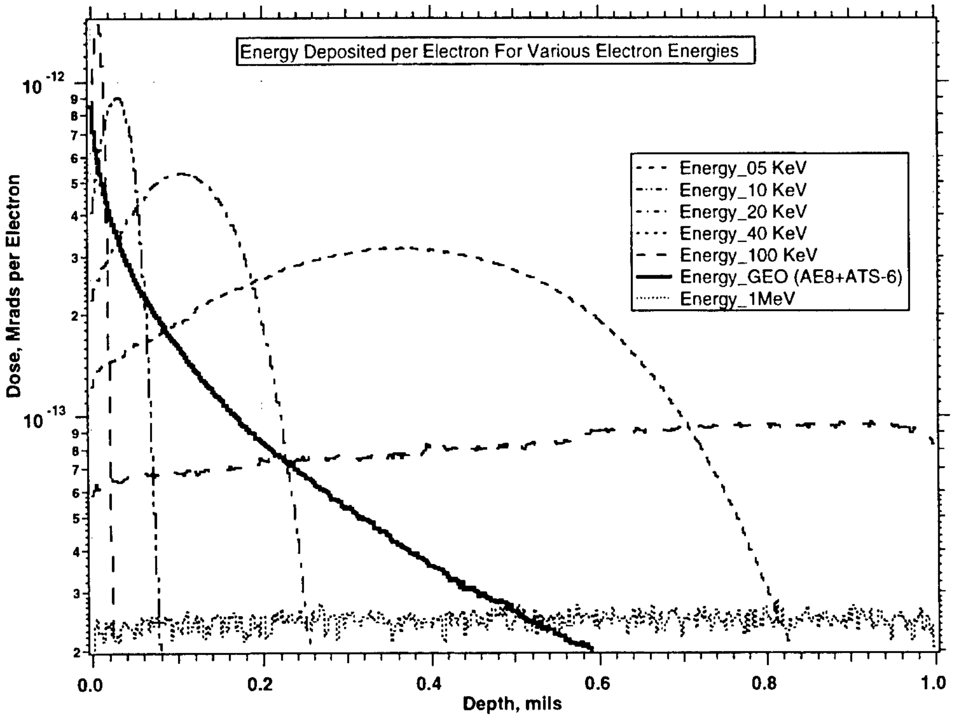

Figure 11. Energy deposition for various electron energies compared to orbital energy deposition.

The prediction curves are shown in Figure 11 for low Earth orbit exposure, Figure 12 for MEO exposure, Figure 13 for a HEO orbit, and Figure 14 for geosynchronous orbit. The GEO case is particularly interesting since it represents a worst-case condition and can be used to envelope other orbital conditions for material confidence testing. Typical test times can be calculated from the fluences required for the simulation. Table 3 shows typical test times and dose rates for a GEO exposure. (1.0 nA/cm^2 is 6.25 E+09 electrons /cm^2/s). It will be seen that a GEO exposure for five years takes about 10 weeks in the lab at reasonable dose rates.

Table 3. Fluences, Dose Rates, and Exposure Times For a GEO Simulation.

Energy (keV)	Fluence (electrons/cm^2)	Dose Rate (nA/cm^2)	Time (h)	Time (days)
100	1.00 E16	1.5	296.3	12.4
40	2.30 E16	2.0	511.1	21.3
20	5.10 E16	10	226.7	9.4
10	8.00 E16	10	655.6	14.8
5	7.20 E16	10	320	13.3

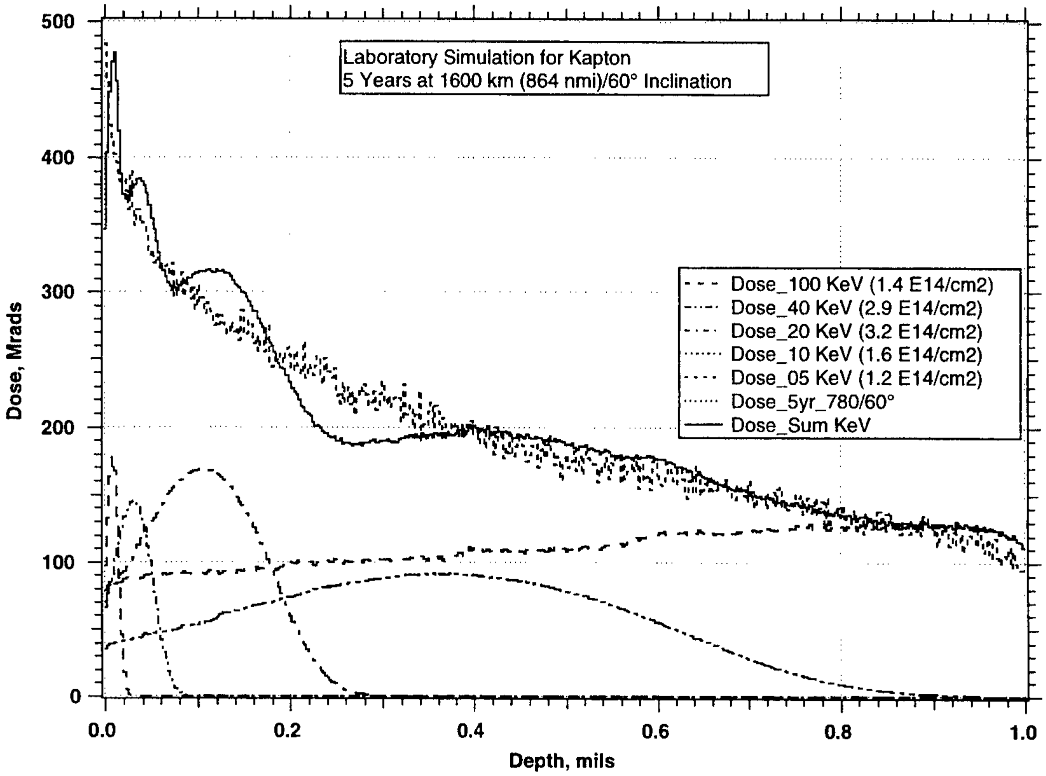

Figure 12. Predicted simulation dose profiles and orbital dose profile for MEO orbit.

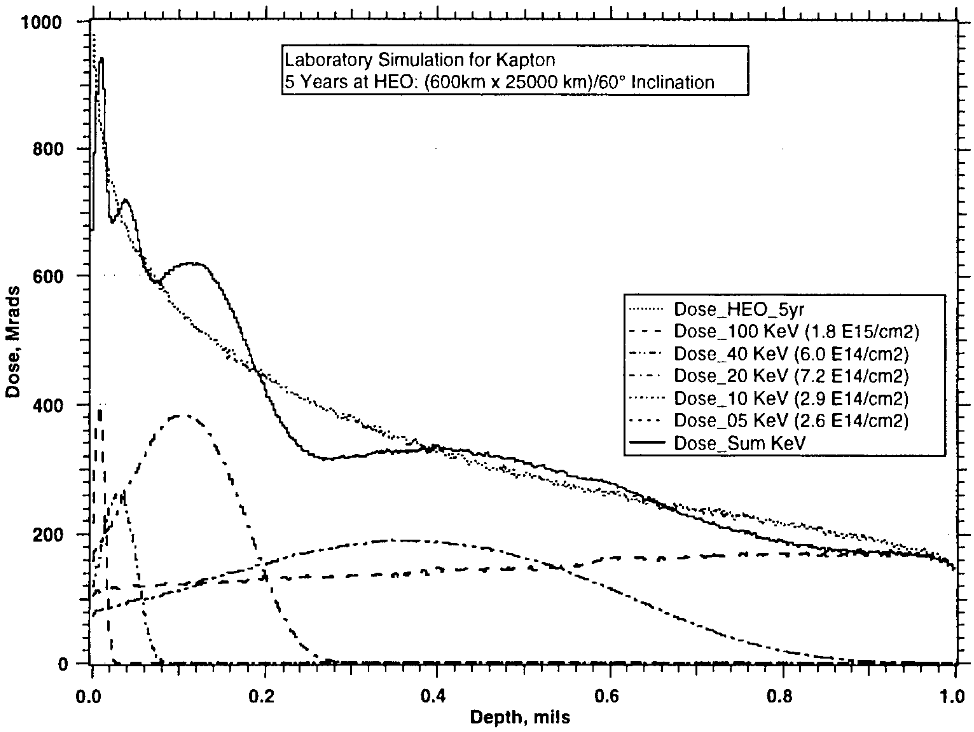

Figure 13. Predicted simulation dose profiles and orbital dose profile for HEO orbit.

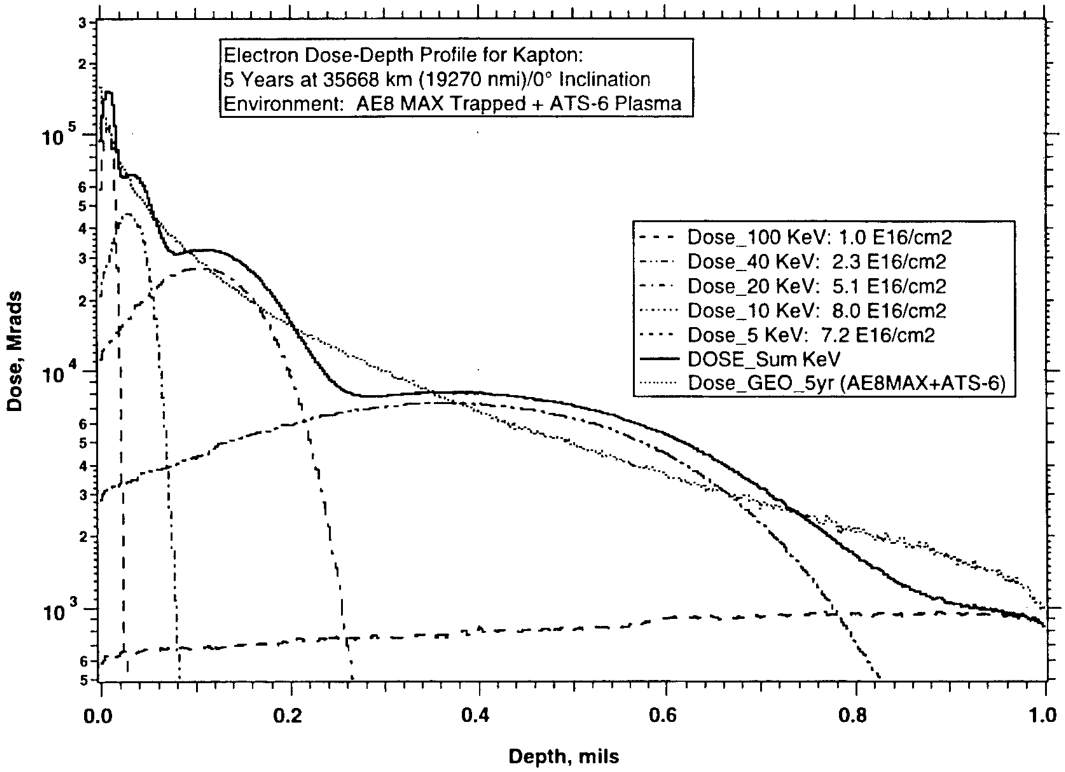

Figure 14. Predicted simulation dose profiles and orbital dose profile for GEO orbit.

6. Summary

The effect of the space environment is an important issue in achieving long lifetimes for inflatable structures. While the use of thin polymer sheets and thin composite structures makes the inflatable structures lightweight, the importance of what is usually a surface dose in radiation becomes much more significant. The effects in thin sheets have been emphasized because the high surface dose due to absorbed radiation makes the radiation levels very high in these thin materials. Similar depth-dose curves are obtained in rigidizable structures in inflatable systems, but the lower sub-surface radiation levels make them more tolerant. Thermal control coatings or multi-layer insulation may also reduce absorbed doses. However, the effects of the space environment needs to be considered for both the thin sheets that might be used for reflectors, sun shields, sails, or other thin, lightweight applications, as well as the rigidized components that would be used as the support structure.

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