

Technical Memorandum 4236

Preliminary Analysis

of a Radiobiological

Experiment for LifeSat

by Lawrence W. Townsend, John E. Nealy,

William Atwell, and Walter Schimmerling

(NASA-TM-4236) PRELIMINARY ANALYSIS OF A
RADIOBIOLOGICAL EXPERIMENT FOR LIFESAT

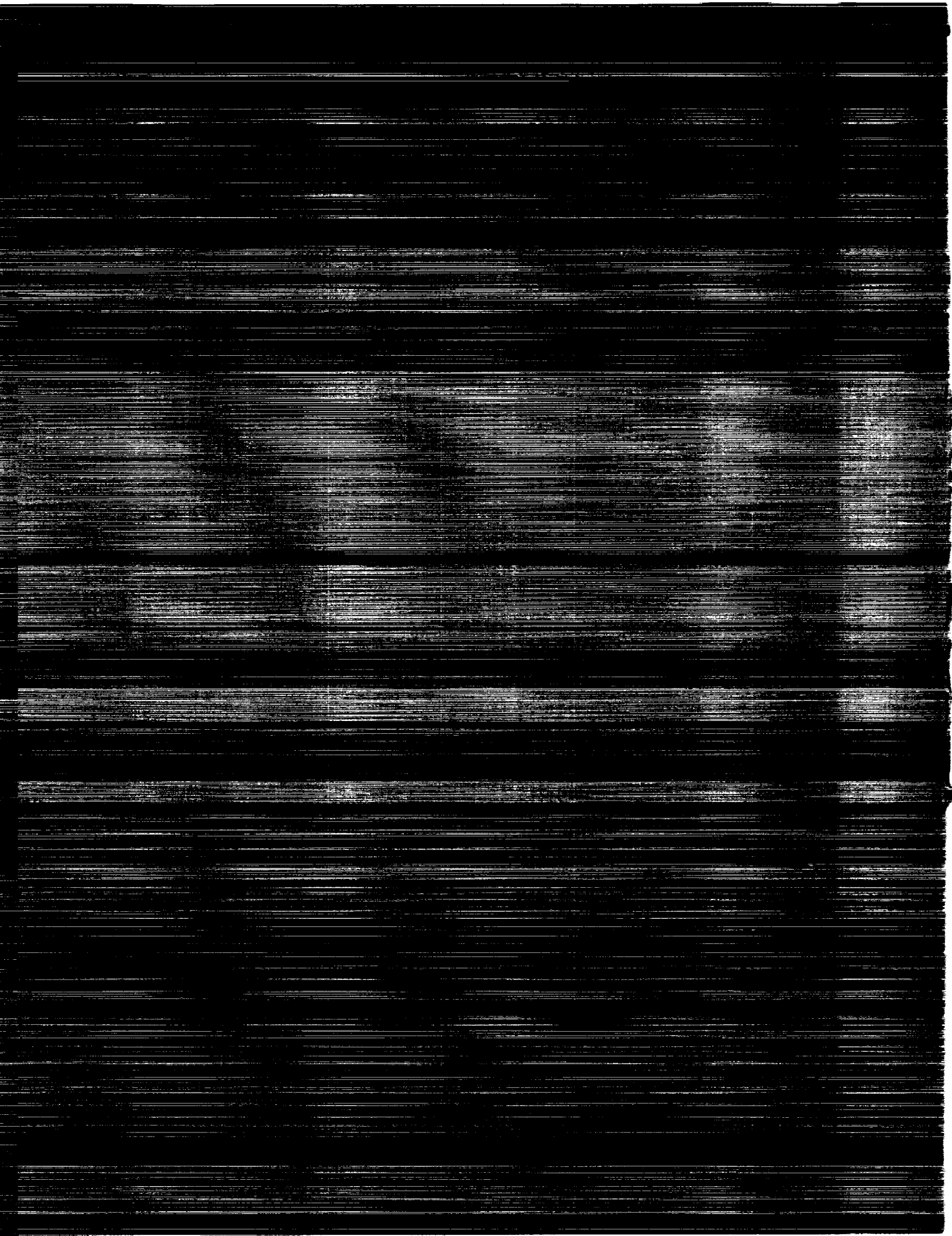
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Introduction

With the possibility of performing radiation life science experiments on a dedicated satellite (LifeSat) in space, a combined effort in radiation physics and radiation dosimetry, in addition to radiation biology, is clearly required to ensure that meaningful biological experiments can be performed. To better understand the relationship of these disciplines, we examine some possible LifeSat missions. As a trial biological system, we consider tumorigenesis in the Harderian gland of mice, a system of sufficient radiosensitivity for which the relative biological effectiveness (RBE) is well-defined by laboratory experiments.

The purpose of this analysis is to determine if statistically meaningful experiments can be performed in Earth orbit that will define the radiological response of such a biological system to radiation exposures in space. The missions examined include circular polar orbits at 200- and 900-km altitudes and a highly eccentric equatorial orbit with perigee and apogee of 400 km and 36 000 km, respectively. The predicted exposures for these orbits are used to estimate incurred doses, which are then related to experimental measurements of the response of the Harderian gland.

Radiation Response of Harderian Gland

The dose response of Harderian tumorigenesis has been measured for ^{60}Co γ and several ions. The experimental procedures and radiation response are discussed in detail by Fry et al. in reference 1. The approximate response is given as

$$P = 2.5 + 50 \left[1 - \exp\left(\frac{-D}{D_o}\right) \right] \quad (1)$$

where the percent of tumor prevalence P at 600 days after exposure is given in terms of a radiosensitivity parameter D_o and the dose D . The spontaneous tumor rate is the leading coefficient representing 2.5 percent. Note that only one-half of the animals appear susceptible to tumor inclination, or else the radiation may have inactivated pretumorous cells. (See Fry et al. in ref. 1.) The value of D_o depends on the ion type for which the RBE is found as a ratio to the reference radiation value of D_o . The measurements of Fry et al. are all given in figure 1 on a common equivalent dose basis with $\text{RBE} = 28.5$. The ion types, their linear energy transfer (LET), the RBE, and the radiosensitivity parameter D_o are listed in table 1. The relation between RBE and LET (where LET is denoted by L) for the various ions is shown in figure 2. In order to interpolate between

data points, we use the function

$$\text{RBE} = 0.95 + \frac{a_1}{L} \left[1 + 2 \exp\left(\frac{-L}{14}\right) \right] \times \left[1 - \exp\left(-a_2 L^2 - a_3 L^3\right) \right] \quad (2)$$

where

$$\left. \begin{aligned} a_1 &= 18\,720 \\ a_2 &= 7.4 \times 10^{-6} \\ a_3 &= 1.14 \times 10^{-8} \end{aligned} \right\} \quad (3)$$

and L (or LET) is given in units of keV/μ .

Equation (1) provides a basis for additivity. The probability of radiation-induced tumors within the susceptible population is

$$P_r = 1 - \exp\left(\frac{-D}{D_o}\right) \quad (4)$$

for which the probability of being among the unaffected population is

$$Q = \exp\left(\frac{-D}{D_o}\right) \quad (5)$$

Consider two exposures with two different ion types. The probability of being unaffected by the first ion type is

$$Q_1 = \exp\left(\frac{-D_1}{D_{o1}}\right) \quad (6)$$

The probability that the unaffected population after exposure D_1 is unaffected by exposure D_2 is then

$$Q_2 = \exp\left(\frac{-D_2}{D_{o2}}\right) \quad (7)$$

so that the total unaffected population from the two exposures is

$$Q_{1,2} = Q_1 Q_2 = \exp\left[-\left(\frac{D_1}{D_{o1}} + \frac{D_2}{D_{o2}}\right)\right] \quad (8)$$

Therefore, the total radiation-induced prevalence is

$$P_{r,1,2} = 1 - \exp\left[-\left(\frac{D_1}{D_{o1}} + \frac{D_2}{D_{o2}}\right)\right] = 1 - \exp\left(\frac{-M}{D_{o1}}\right) \quad (9)$$

where

$$M = D_1 + \frac{D_{o1}}{D_{o2}} D_2 \quad (10)$$

The RBE with exposure 1 taken as the reference radiation is

$$\text{RBE} = \frac{D_{o1}}{D_{o2}} \quad (11)$$

and is found by Fry et al. to be LET (or L) dependent.

The generalized effective dose M in units of rem (radiation equivalent in mice) is given by

$$M = \sum_i \int \text{RBE} [L_i(E)] S_i(E) \phi_i(E) dE \quad (12)$$

where $S_i(E)$ is the stopping power of ion i at energy E and ϕ_i is the ion fluence after which the prevalence can be determined from equation (1) with $D_o = 770$ rem. The unit rem is taken as the equivalent ^{60}Co γ dose in units of cGy.

The Environment

We assume that no significant solar flare events occur during a 60-day mission of LifeSat. This leaves the galactic cosmic rays (GCR) and trapped radiations for consideration. In order to examine a range of exposure conditions, we look to three possible 60-day missions:

1. An elliptic equatorial orbit of 400-km perigee and 36 000-km apogee
2. A circular polar orbit at 900 km
3. A circular polar orbit at 200 km

The highly eccentric equatorial orbit should provide the highest GCR contribution, whereas the 900-km circular polar orbit should result in lower, but still significant, GCR exposures. The quiet-time, geomagnetic transmission factors for the three orbits are shown in figures 3-5. (We used the Naval Research Laboratory cosmic ray effects on microelectronics (NRL CREME) model of ref. 2.) We see that the equatorial orbit is effectively outside the magnetic field a large percentage of the time so that even three out of four 400-MeV protons (with a rigidity of approximately 1 GV) in free space hit the satellite. In contrast, only one out of four 400-MeV protons is able to penetrate to the 900-km polar orbit. The 200-km polar orbit experiences the Earth's shadow more than the 900-km orbit, which accounts for differences in the rigidity functions of figures 4 and 5. The trapped-particle environment has been taken from the standard models AP-8 (ref. 3) and AE-8 (personal communication with J. I. Vette of the NASA Goddard Space Flight Center in 1984) from which flux distributions of protons and electrons are provided as a function of geomagnetic field strength. The contributions of the trapped radiations to the exposure for the three orbits are also quite different. The elliptic equatorial orbit is predominantly exposed to energetic electrons, whereas the polar

orbits are exposed mainly to trapped inner-zone protons.

Preliminary Analysis of Space Experiments

The relevant dosimetric quantities are evaluated for the various environments as a function of shield thickness. For the trapped radiations, a version of the National Bureau of Standards (NBS) code SHIELDDOSE (ref. 4) has been utilized, which includes contributions from electrons and electron bremsstrahlung. The GCR exposures and doses are calculated with the Langley heavy ion GCR code (see, e.g., ref. 5) using free-space GCR spectra appropriately modified by the transmission functions of figures 3-5. The variation of dose as a function of aluminum shield thickness t is shown in figure 6. The GCR exposures are expressed in equivalent ^{60}Co γ dose units (herein called rem) for which the physical dose is a factor of 6 to 8 lower than the equivalent dose. (The average RBE is about 8 at 1 g/cm² and drops to 6 at 5 g/cm².)

If one considers doing a 10-animal experiment, then a prevalence rate on the order of 30 percent or more would be required. Such levels are easily achieved in the 400-km by 36 000-km equatorial orbit, as seen in table 2.

Furthermore, when one considers that the mean instantaneous (approximately 1 min) X-ray dose to produce lethality in mice is 550 rad (ref. 6), it may be that special shielding may be required to provide adequate protection of the lives of the animals being tested. However, when the exposure occurs continuously over an extended period, the mean lethal dose increases. (For example, the mean lethal dose is approximately 1200 rad for a 30-day exposure, as shown in ref. 6.) Thus, the results of table 2 indicate that for the eccentric orbit, shielding in excess of 3 g/cm² is required for specimen survivability.

For the 900-km polar orbit, effective shielding amounts somewhat less than 1 g/cm² may be required to obtain the desired response. Also, the dose rate may be increased by placement of the satellite in a higher-altitude orbit. The very low total doses predicted for the 200-km orbit suggest that this deployment may serve as a control experiment.

Concluding Remarks

A preliminary analysis of potential biological experiments for LifeSat flights is presented in terms of 60-day exposures of the very sensitive Harderian gland of a mouse to the space radiation environment. It is predicted that statistically meaningful results may be obtained for polar orbits of moderately high

altitude (900 km or more) or for very eccentric equatorial orbits (400 km by 36 000 km) that may provide high dose rates and substantial exposure to the free-space cosmic ray environment. The variation of dose for both trapped and cosmic ray sources has been computed for a range of aluminum shield amounts. Effective shield thicknesses up to 3 g/cm² are indicated as providing the approximate desired 60-day mission dose. The present results may provide a basis for more detailed shield studies that account for the specific satellite configuration.

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Table 1. Radioparameters of Harderian Gland

Radiation type	LET, keV/ μ	RBE	D_o , cGy
$^{60}\text{Co } \gamma$	0.2	1	769.5
^4He	18	5	153.9
^{12}C	80	11.2	68.7
^{20}Ne (plateau)	25	6	128.3
^{20}Ne (distal)	190	28.5	27
^{40}Ar	6540	28.7	26.8

Table 2. Total Dose Equivalent and Predicted Prevalence of Harderian Tumors for 60-Day Mission

Aluminum shield thickness, t , g/cm ²	400 km by 36 000 km (equatorial orbit)		900 km (polar orbit)		200 km (polar orbit)	
	M , rem	P , percent	M , rem	P , percent	M , rem	P , percent
1	9000	(52.5)	300	(18.6)	19	(3.7)
2	2414	(50.3)	210	(14.4)	7.7	(3.0)
3	1200	(42.0)	168	(12.3)	6.2	(2.9)
5	690	(32.1)	129	(10.0)	5.3	(2.8)
10	354	(20.9)	82	(7.5)	4.6	(2.8)

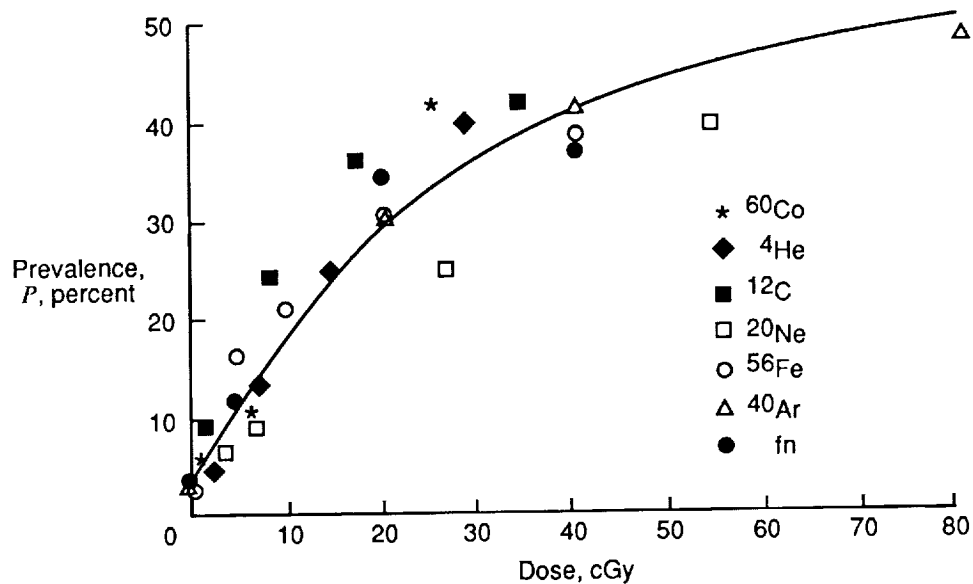


Figure 1. Dose response relationship of reference 1 for Harderian gland tumor from various radiations on a common equivalent dose basis with $\text{RBE} = 28.5$. The symbol fn refers to fission neutrons.

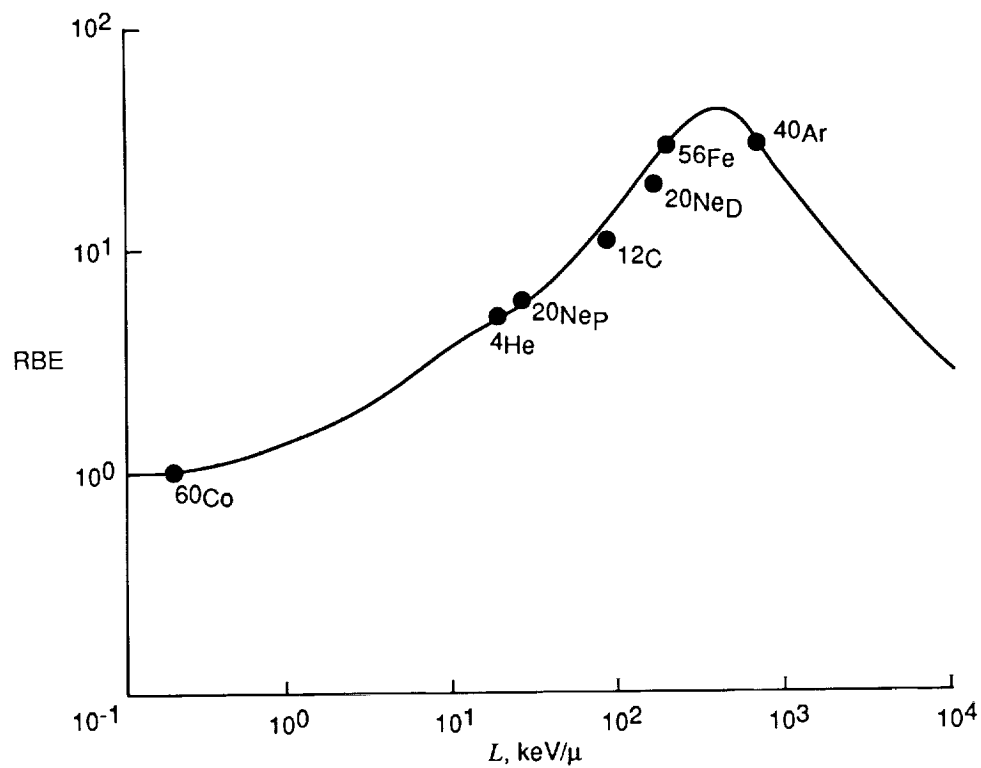


Figure 2. Relation between RBE and LET (denoted by L) measured by Fry et al. (ref. 1) for various radiations. The symbols P and D refer to the plateau and distal regions, respectively, of the Bragg curve.

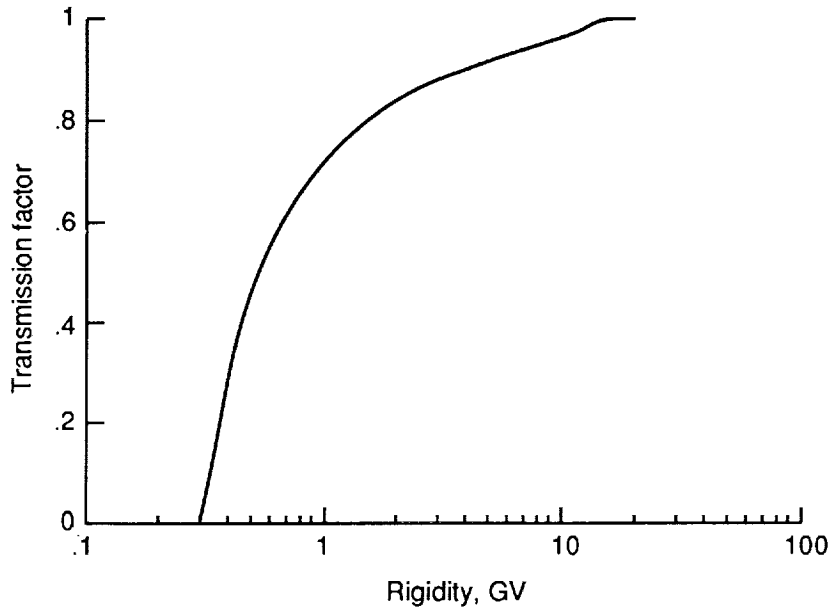


Figure 3. Geomagnetic transmission factor for equatorial orbit of 400-km perigee and 36 000-km apogee.

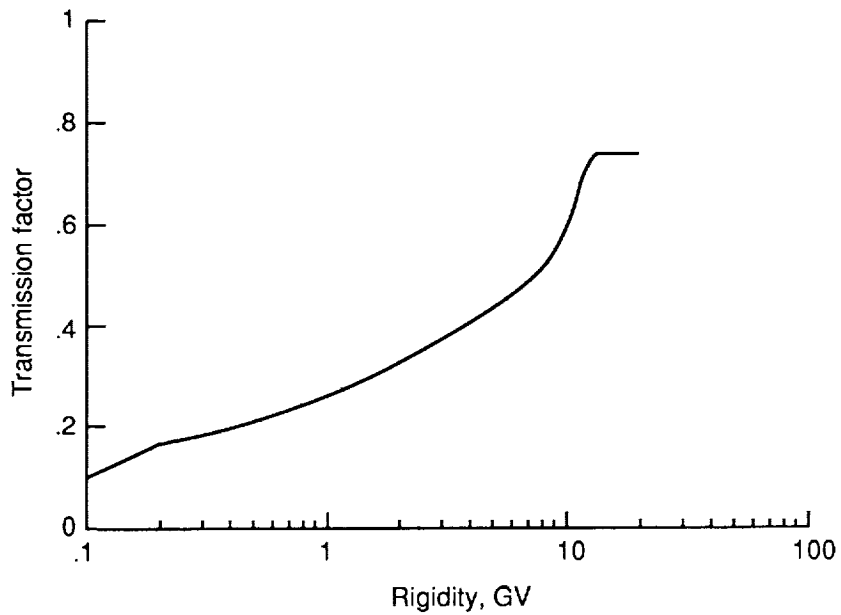


Figure 4. Geomagnetic transmission factor for circular polar orbit at 900 km and 90° inclination.

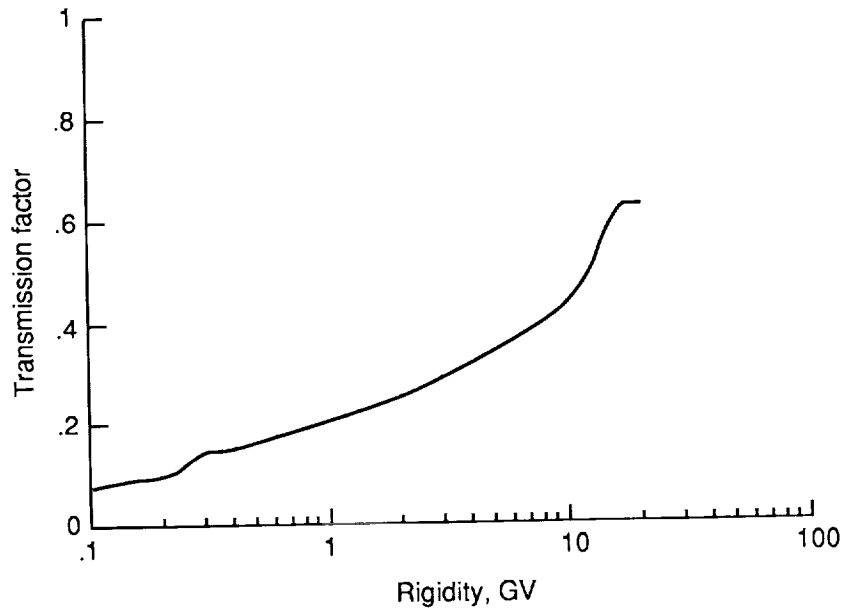


Figure 5. Geomagnetic transmission factor for circular polar orbit at 200 km and 90° inclination.

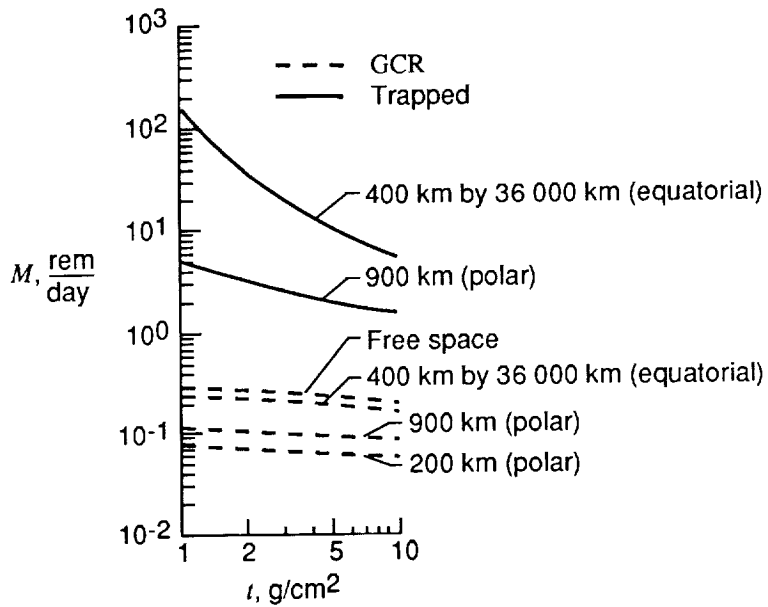


Figure 6. Equivalent ⁶⁰Co γ dose for LifeSat missions. For 400 km by 36 000 km equatorial orbit, inclination angle is 0°.





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