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Dose in Critical Body Organs in Low Earth Orbit

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SUMMARY

Human exposure to trapped radiations in low Earth orbit (LEO) is evaluated on the basis of a simple approximation of the human geometry for spherical shell shields of varying thickness. A data base is presented that may be used to make preliminary assessment of the impact of radiation exposure constraints on human performance. A sample impact assessment is discussed.

INTRODUCTION

With the advent of the Space Transportation System, there is rapid advancement in utilization of space in low Earth orbit (LEO). Principal interest in LEO is the development of human capabilities, observation satellites and large space antennas. Increasing power requirements to promote manned capability and space industrialization are demanding large area solar arrays in addition to large components of living and work quarters. The net effect is increased atmospheric drag requiring higher orbital altitudes and greater radiation exposure. Furthermore, the increased emphasis on erectable structures places greater demands on human performance in extravehicular work activity (EVA).

In planning such missions, it is necessary to consider the impact of radiation exposure on mission activity. It is the purpose of the present report to present environmental data in a format which is easily utilized in mission analysis. The geometric models of the spacecraft and the human body are simplified to provide first-order estimates of limits for planning purposes. The present models are based on time-averaged exposure rates without regard to important time variations in exposure. Such time variations can often be used to reduce exposure during specific mission tasks. If exposure limits are approached during the mission planning stage, this is an indication of the need for a detailed study of the impact of exposure limitation.

RADIATION EXPOSURE CONSTRAINTS

Radiation exposure constraints have been established on the basis of relative tissue sensitivities and scale of hurt (ref. 1). It was assumed that the rate of induction of solid tumors was equal to the rate of induction of leukemia and that the doubling dose was 400 rems (ref. 2). The derived exposure constraints are given in table 1 for unit reference risk (induced rate equals natural spontaneous rate) and are those presently in force in the space program. More recently it has been found that the solid tumor incidence rate is four times greater than the leukemia rate (ref. 3) and allowable dose constraints for the space program are likely to be reduced considerably. Meanwhile the values in table 1 will be used in space mission studies.

The quality factors (scale factor for relating physical dose to biological dose) for the LEO environment are not known. Techniques for calculating quality factors are available only for energetic protons aftera thickness of tissue equivalent material (refs. 4 and 5). Quality factors for aluminum shields are yet to be derived. Benton and Henke (ref. 6) assume QF ≈ 1.5 for radiations in LEO which appear unnecessarily conservative compared to the QF ≈ 1.3 for solar cosmic rays (ref. 7).

SPACECRAFT SHIELDING

Spacecraft are complex geometric structures for which specific exposure relations within the interior are difficult to define exactly. A family of approxmate methods have developed over the years which have resulted in great simplification. The methods result from the well-known straight-ahead approximation of heavy charged particle transport (ref. 8) and are found to be useful even for electron shield approximation (ref. 9). A recent investigation by Jordan further explores the value of these methods (ref. 10).

Central to these approximations is the distribution of material about the point of interest. These are usually presented as areal density distribution functions which give areal density as a function of the fraction of solid angle (ref. 11). Areal density distributions for the Apollo command module showed minimum shield thickness of about 6 g/cm^2 (Al) with 80 percent of all directions seeing more than 7.5 g/cm^2 (Al). In contrast, the Skylab had minimum thickness due to windows of 0.5 g/cm^2 (Al) and 75 percent of the shielding on the order of 1 g/cm^2 (Al). It is herein assumed that a large habitat can be approximated by a spherical shell with the astronaut at the center. This is a maximum exposure for such a spherical configuration.

ASTRONAUT SELF-SHIELDING

The human body is a complicated geometric arrangement and the specific organs of interest are likewise distributed in complex geometric patterns. Detailed man models have been derived (ref. 11) and substantially improved (ref. 12). To approximate the dose to various body organs, we use the work of Billings and Langley (ref. 13) in which a simple spherical shell model of critical body organs are derived. This model is represented by spherical shell thickness equivalent to the depth of the organ and a coefficient representing the amount of radiation incident on the organ in question. The model utilized here is the minimum-number proton dosimeters parameters (table 3 of ref. 13) except for the skin dose which utilizes the minimum-error parameters (table 2 of ref. 13). The skin dose is approximated by a dosimeter radius

$$r = \begin{cases} z/4 & z \leq 8 \text{ g/cm}^2 \\ z & z > 8 \text{ g/cm}^2 \end{cases} \tag{1}$$

with coefficient

$$C(z) = a + b\, e^{-\alpha z} \tag{2}$$

where z is the vehicle shield thickness. The remaining organs are correspondingly approximated for a constant r shown in table 2 along with the coefficients a, b, α used in the present calculations.

Environmental Data

In the present calculations, the radiations other than those trapped in the Earth's magnetic field are ignored. The solar cosmic rays (SCR) can be quite important for orbits inclined by more than 50° (ref. 14). Galactic cosmic rays (GCR) contribute at levels of 30 mrad/day or less depending on inclination. The GCR background is low but poses a significant biological problem, especially for long-term exposure, due to the presence of heavy ions. Heavy ion exposure constraints are presently unspecified and are ignored in this study.

The trapped particle fluence is taken from a compilation of data (ref. 15) derived form the AE4, AE5 electron models and AP5, AP6, AP7 proton models for solar maximum. These data are quite different from the results of reference 16. A comparison of the environmental data of references 15 and 16 are given in table 3. The electron data of Stassinopoulos at 30°, in particular, is nearly an order-of-magnitude greater than the data at 28.5° and 35° of Watts and Wright. The origin of these differences are not known to the present authors and we take the data of reference 15 as the basis of the present study.

Method of Calculation

The trapped radiation fluence data are converted to dose in the center of a solid aluminum sphere using the SHIELDOSE program of Seltzer at NBS (ref. 17). The human body geometry and spacecraft geometry are combined according to the joint probability distribution (ref. 13) which for our simplified geometry becomes

$$D_{organ} = C_{organ}(z)\, D_{sphere}(R_{organ} + z) \tag{3}$$

where $C_{organ}(z)$ is the appropriate coefficient of table 2 for the specific body organ, $D_{sphere}(z)$ is the dose in the center of an aluminum sphere of radius z, R_{organ} the corresponding organ radius (table 2), and z is the spacecraft shield thickness assumed to be a spherical shell with the dose point at the center. Results of the calculations are shown in the figures 1 through 19. An approximate meaning is associated with the thicknesses shown in table 4 as noted.

It is seen from the figures that skin dose for EVA at 500 km and 30° inclinations amounts to about 3.4 rad/day by interpolation. Considering that the maximum time in EVA per astronaut is 6 hours/day or 0.9 rad/day for EVA activity--the equivalent of 81 rad is received in the 90-day period of space activity. Hence, only 24 rad of additional skin exposure is allowable and though 0.5 rad/day is received within an 1.0 g/cm^2 habitat during the remaining 18 hours of non-EVA status. The total dose received by the skin for an active EVA crew member is as much as 126 rad in 90 days or approximately the amount allowed by present guidelines assuming a QF of 1 (table 1). If the QF of 1.5 suggested by Benton and Henke (ref. 6) is employed, then dose limits are greatly exceeded for these types of operations in this particular orbit. The importance of knowing with certainty the quality factor in LEO is obvious. It is clear that a careful assessment of radiation exposure for a mission at 500 km and 30° inclined orbits is needed. This is especially true in view of the expected lowering of allowable exposure limits well below those given in table 1.

CONCLUDING REMARKS

The present results provide a data base for making preliminary assessments of exposure constraints on human performance in low Earth orbit (LEO). The present results are to be interpreted in the context of current radiation constraints (table 1) but being mindful of future reductions of on the basis of more recent biological data. It is estimated that exposure limits may be reduced by a factor of four which would greatly impact LEO operations. It is also noted that uncertainties in quality factors behind aluminum shields could have important implications for allowable human activity and need to be more reliably determined for future exposure estimates.

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TABLE 1. - SUGGESTED EXPOSURE LIMITS AND EXPOSURE ACCUMULATION RATE CONTRAINTS FOR UNIT REFERENCE RISK CONDITIONS

		Ancillary reference risks			
Constraint	Primary reference risk (rem at 5 cm)	Bone marrow (rem at 5 cm)	skin (rem at 0.1 mm)	Ocular lens (rem at 3 mm)	Testes (rem at 3 cm)
1-year average daily rate		0.2	0.6	0.3	0.1
30-day minimum		25	75	37	13
Quarterly maximum[a]		35	105	52	18
Yearly maximum		75	225	112	38
Career limit	400	400	1200	600	200

[a]May be allowed for 2 consecutive quarters followed by 6 months of restriction from further exposure to maintain yearly limit.

TABLE 2 - HUMAN BODY GEOMETRY PARAMETERS USED IN PRESENT CALCULATIONS

Organ	r, g/cm^2	a	b	α
BFO	5.5	0.502	0.000	1.0
Testes	5.5	0.641	0.428	0.57
Lens	0.5	0.599	-0.206	0.25
Skin*	z/4	0.720	-0.356	0.493

* $r \leq 2$ g/cm^2

TABLE 3 - Comparison of Environments (inclinations 28.5° and 35°) of Watts and West (ref. 16) to that of Stassinopoulus (inclination 30°, ref. 15)

Proton Fluence, protons/cm^2 - day									
Altitude	200km			400km			800km		
Inclination	28.5°	30°	35°	28.5°	30°	35°	28.5°	30°	35°
10 MeV	4.5E4	1.3E5	2.1E7	1.0E6	2.7E6	2.1E6	2.4E7	4.6E7	2.7E7
50 MeV	1.5E4	2.7E4	3.8E4	5.3E5	1.3E6	9.8E5	1.1E7	1.8E7	1.1E7
100 MeV	5.4E3	9.7E3	1.2E4	2.7E5	6.5E5	4.9E5	6.8E6	1.1E7	7.0E6

Electron Fluence, electrons/cm^2 - day									
Altitude	200km			400km			800km		
Inclination	28.5°	30°	35°	28.5°	30°	35°	28.5°	30°	35°
1 MeV	1.7E3	1.1E4	3.3E3	4.5E5	1.8E7	4.8E6	7.3E7	5.8E7	1.0E8
2 MeV	5.5E2	6.2E3	7.4E2	7.8E4	5.2E6	8.4E5	1.2E7	1.5E8	1.7E7
3 MeV	2.5E2	2.1E3	3.7E2	8.6E3	6.7E5	6.3E4	9.9E5	1.9E7	1.3E6

TABLE 4

z, g/cm^2(Al)	Place of Occurrence
0.2	Spacesuit
1.0	Space Helmet, Skylab wall
2.0	Heavily shielded habitat
5.0	Heavily shielded vehicle, Solar cosmic ray shelter

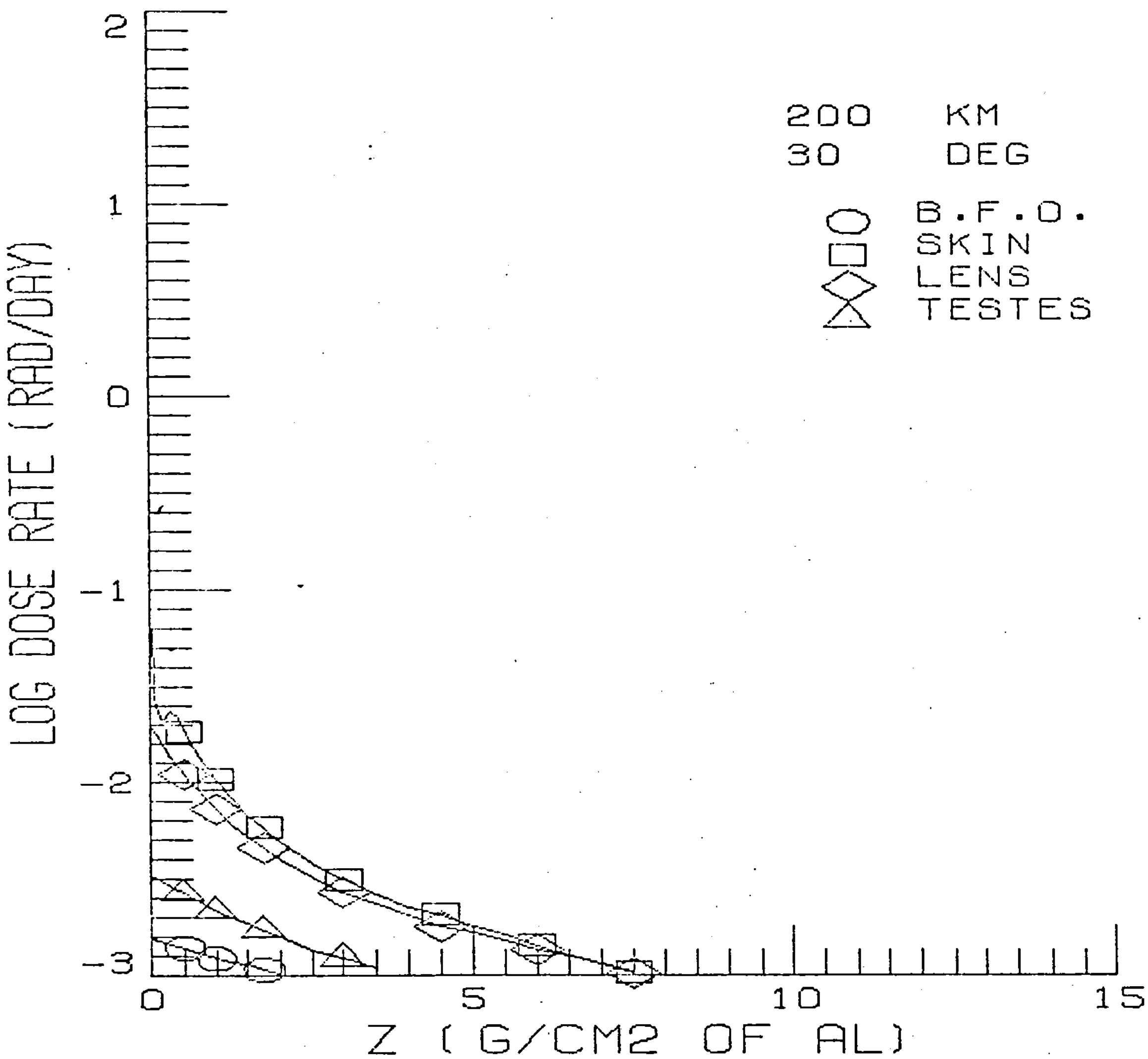

Figure 1.- Dose to critical body organs as a function of shield thickness for 30^0 inclined 200 km circular orbit.

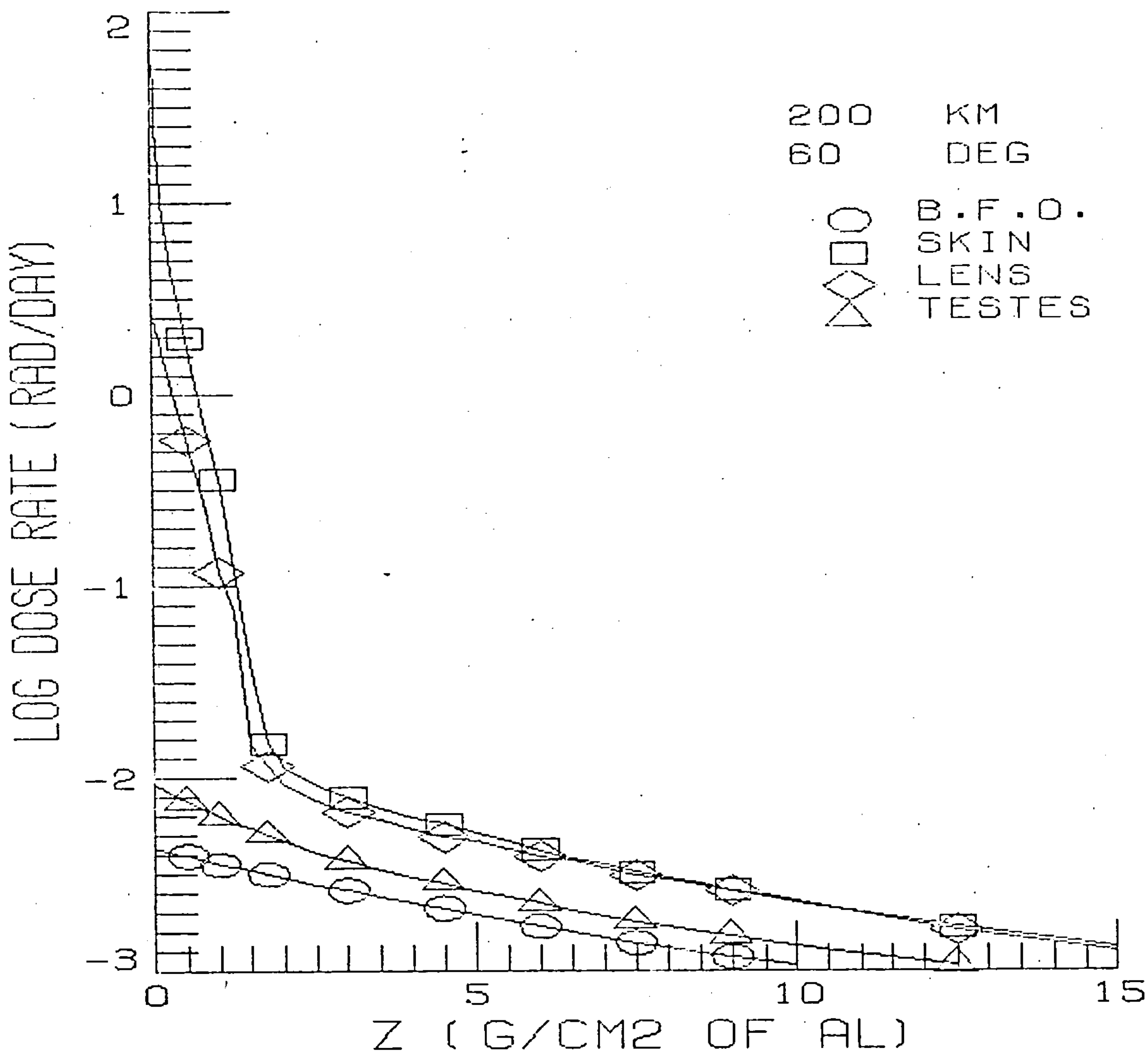

Figure 2.- Dose to critical body organs as a function of shield thickness for 60^0 inclined 200 km circular orbit.

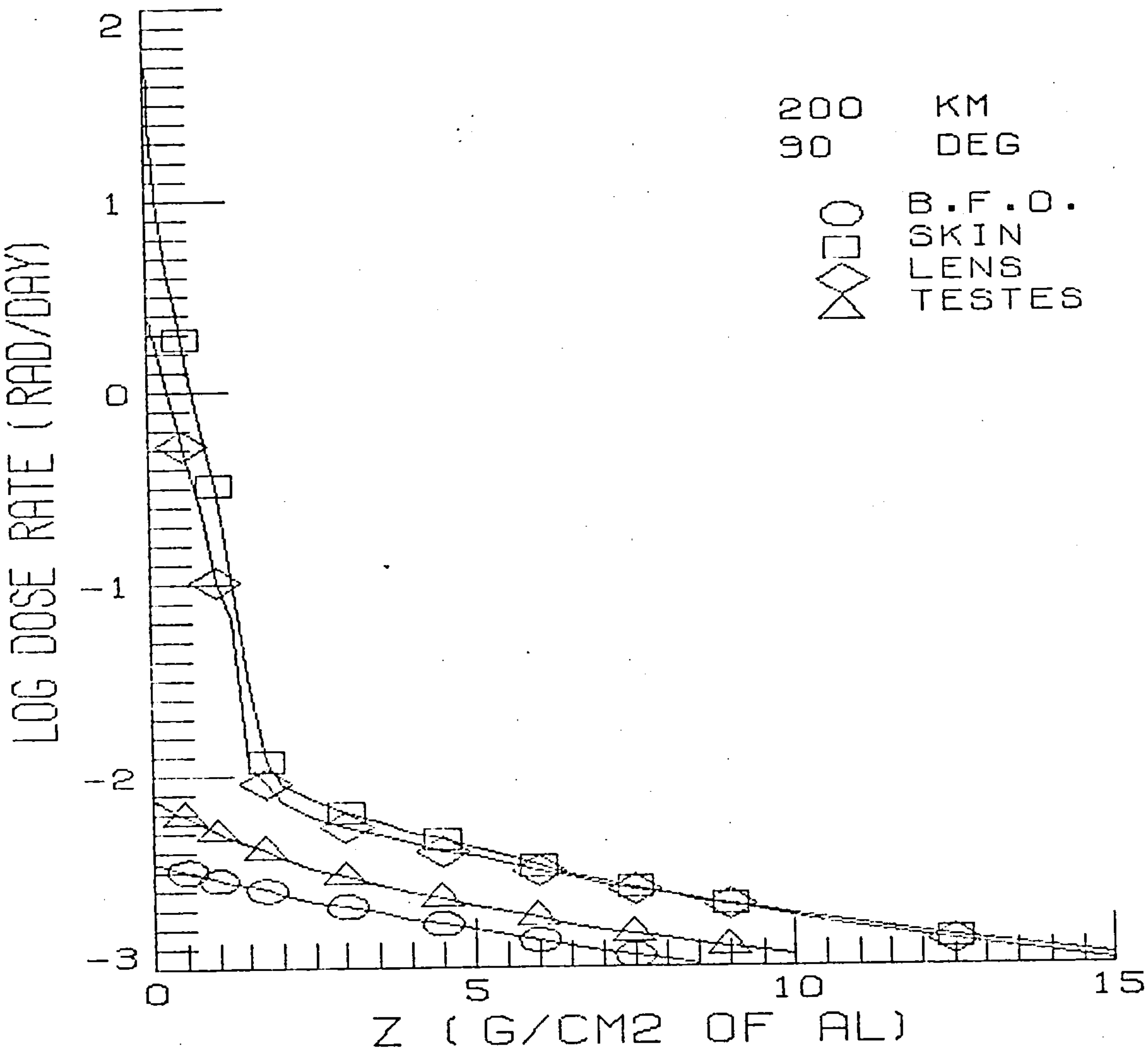

Figure 3.- Dose to critical body organs as a function of shield thickness for 90^{0} inclined 200 km circular orbit.

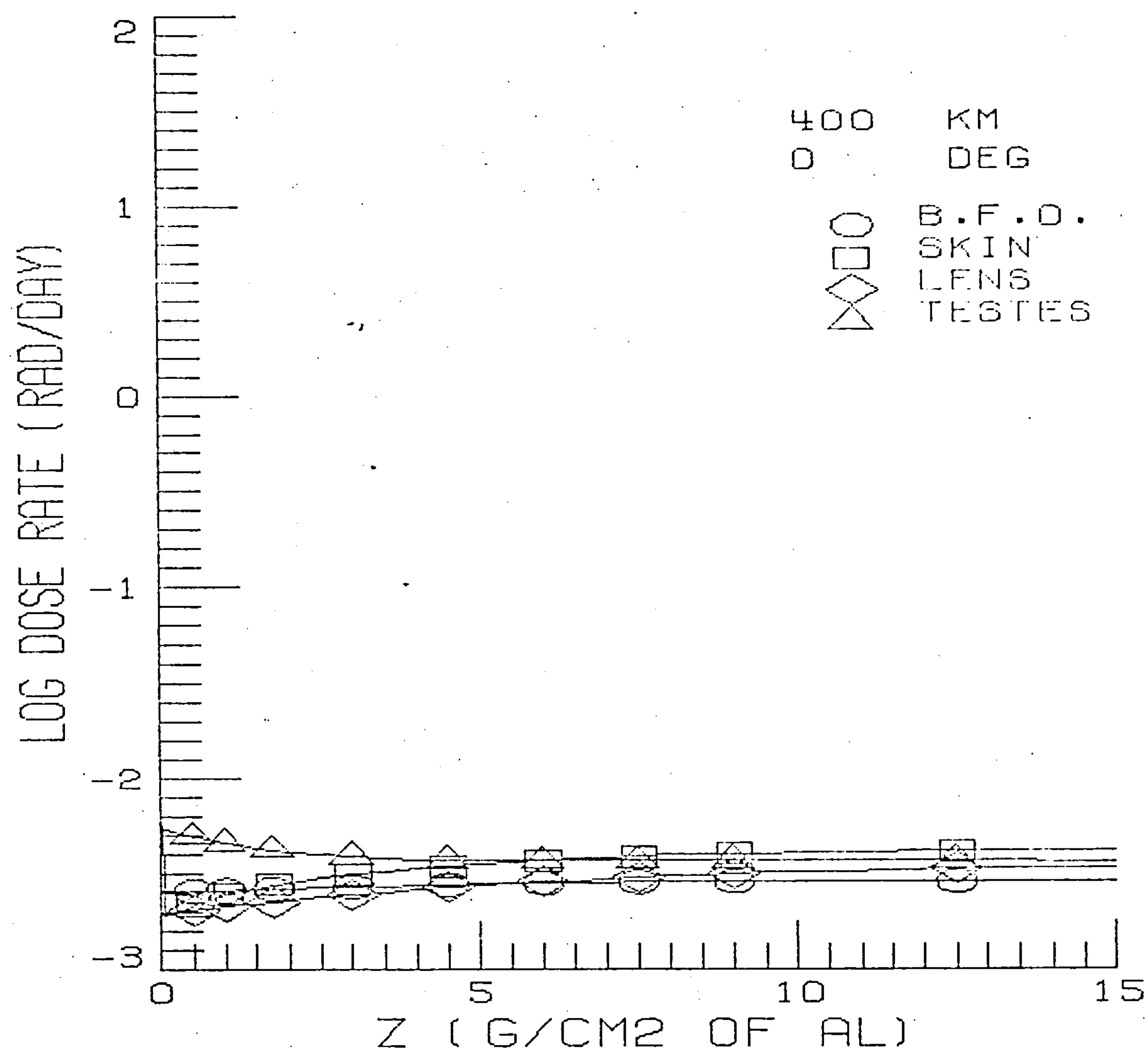

Figure 4.- Dose to critical body organs as a function of shield thickness for 0^{0} inclined 400 km circular orbit.

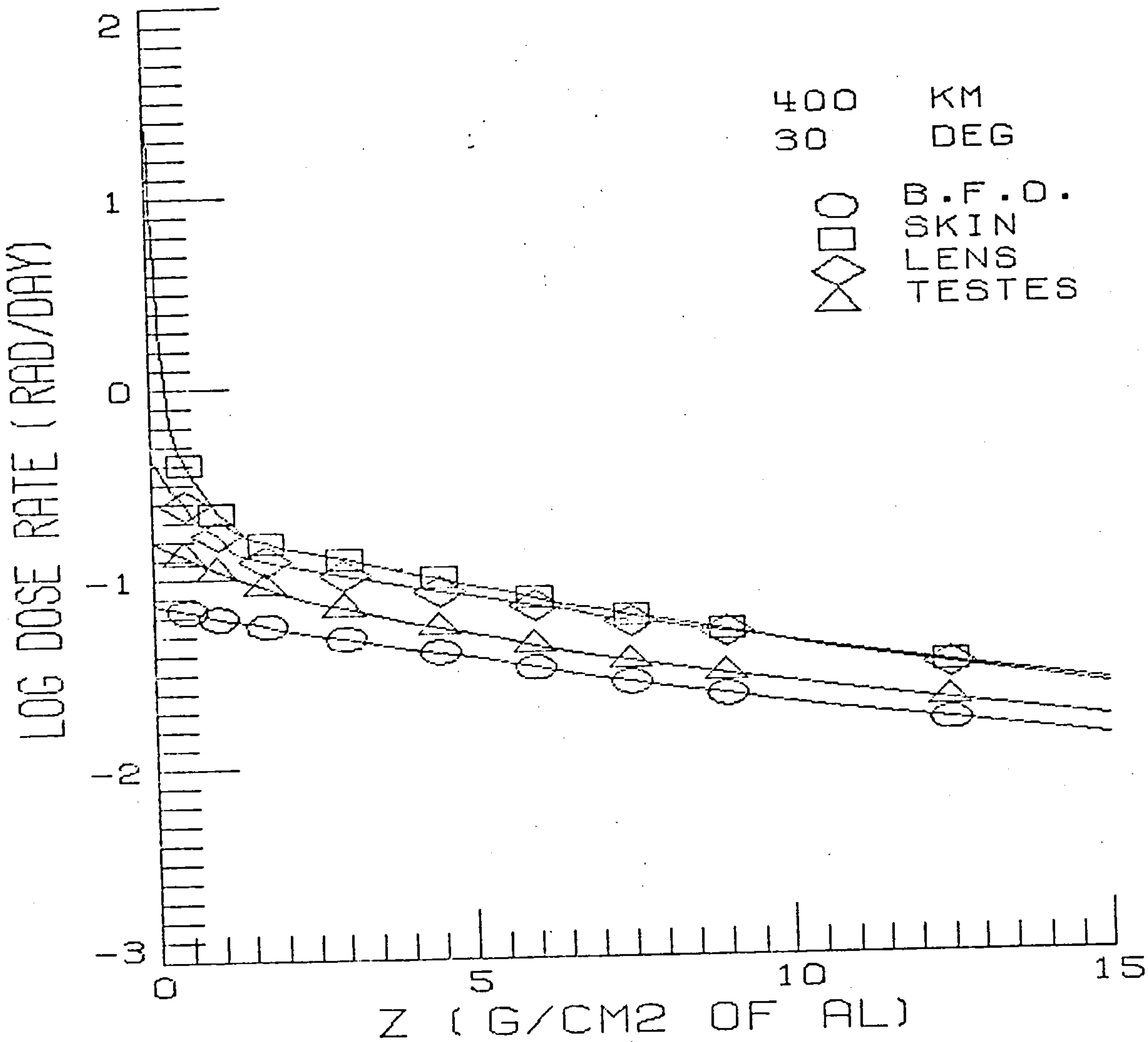

Figure 5.- Dose to critical body organs as a function of shield thickness for 30^0 inclinded 400 km circular orbit.

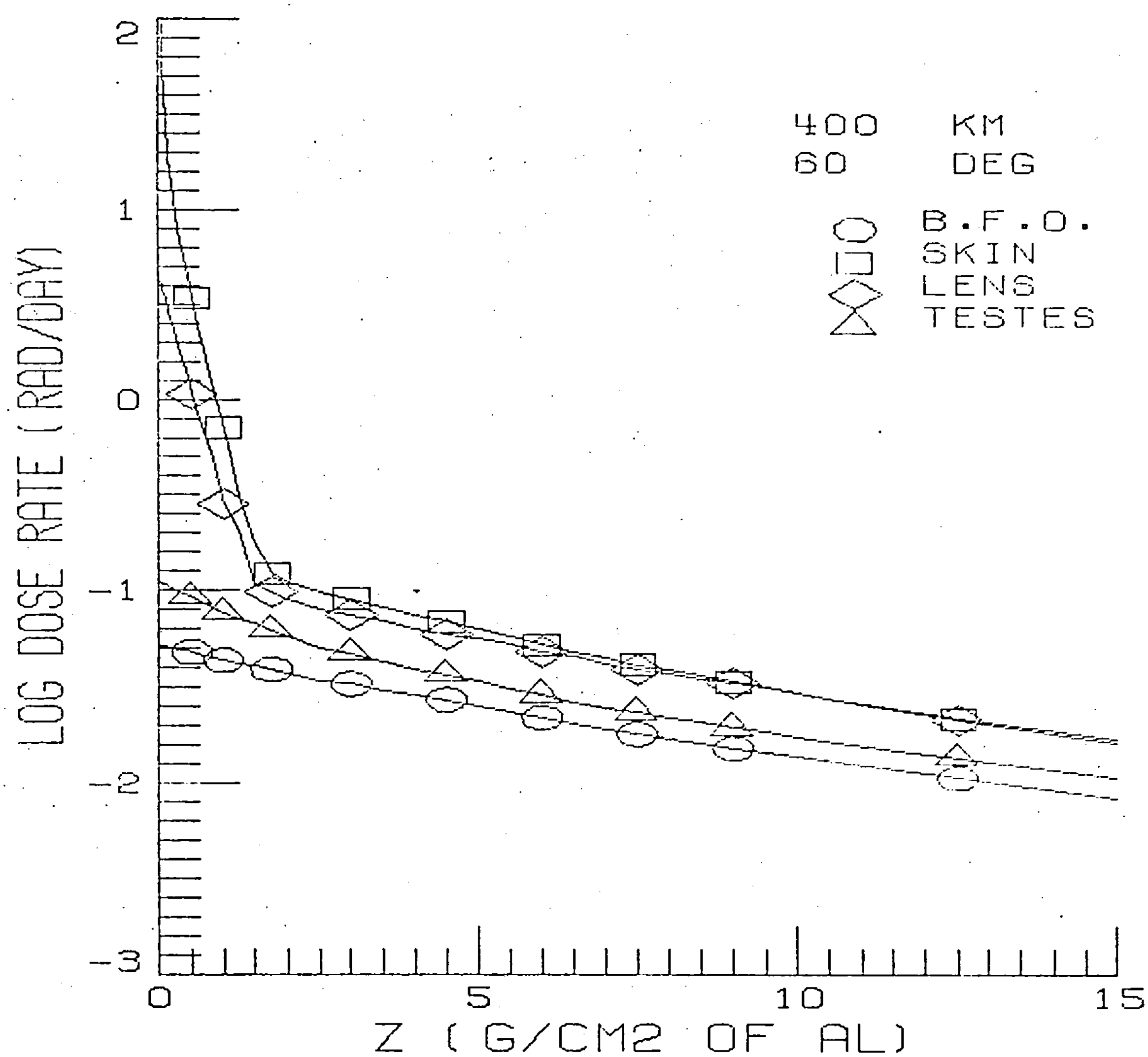

Figure 6.- Dose to critical body organs as a function of shield thickness for 60^{0} inclined 400 km circular orbit.

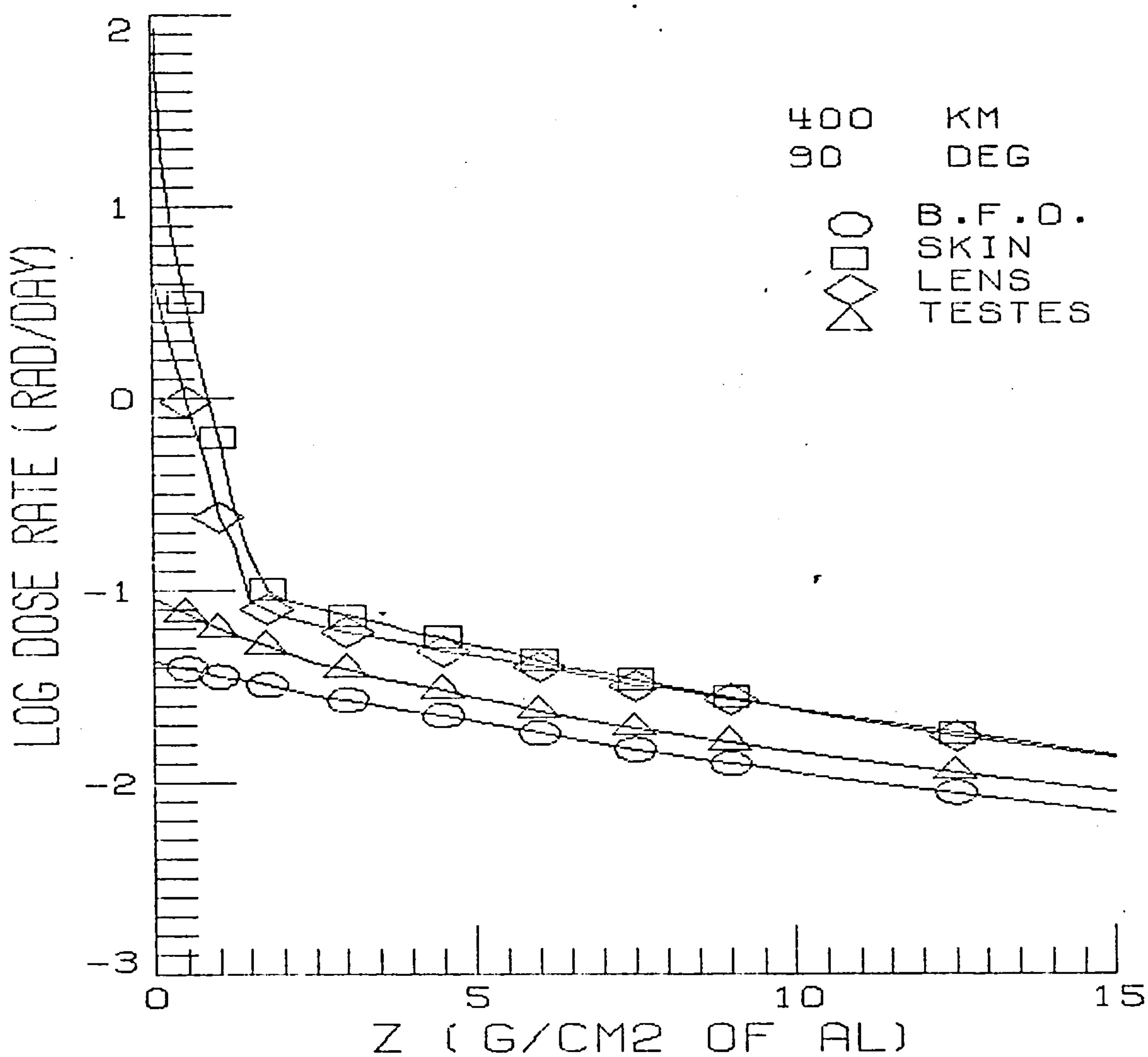

Figure 7.- Dose to critical body organs as a function of shield thickness for 90° inclined 400 km circular orbit.

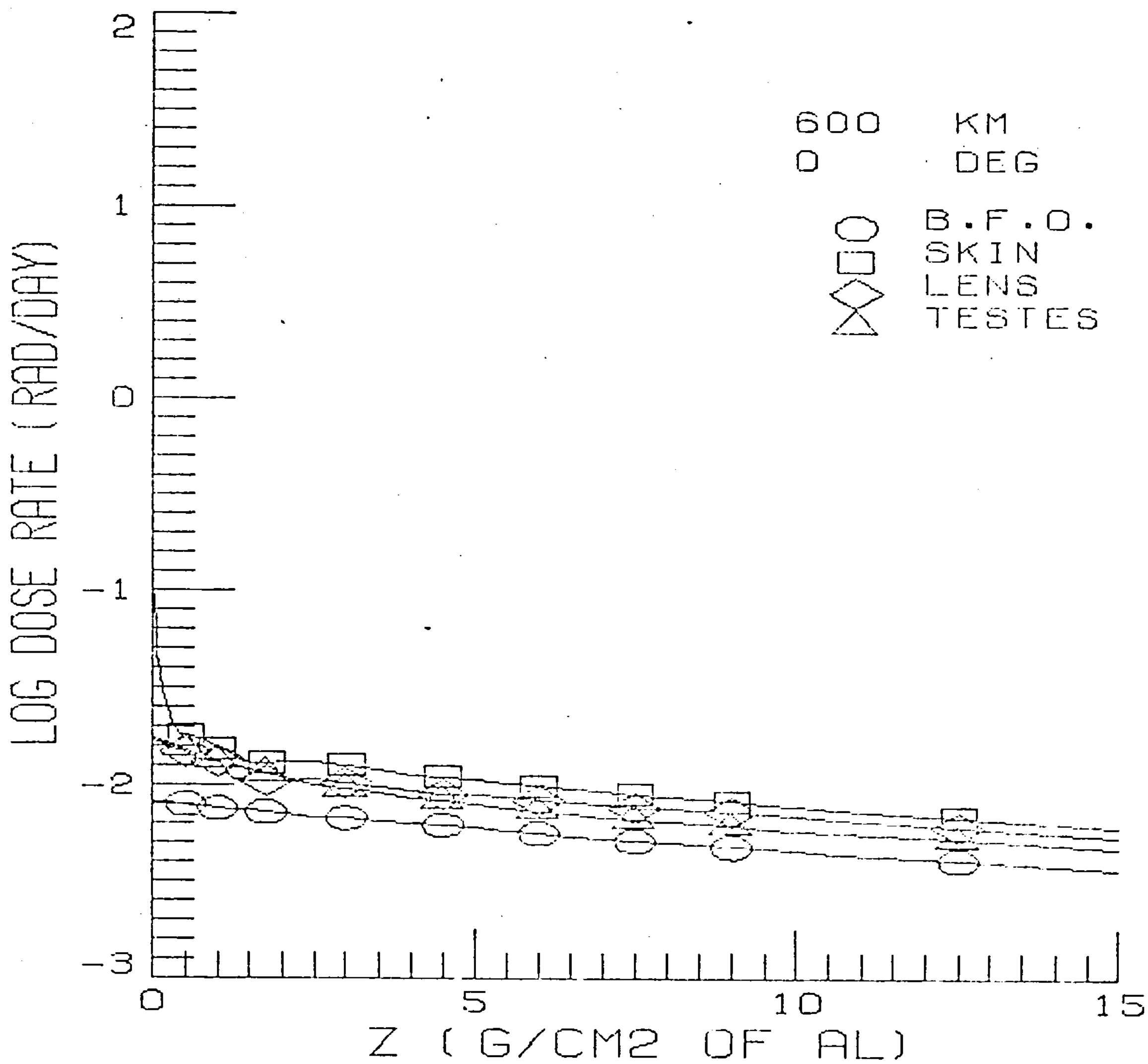

Figure 8.- Dose to critical body organs as a function of shield thickness for 0^{0} inclined 600 km circular orbit.

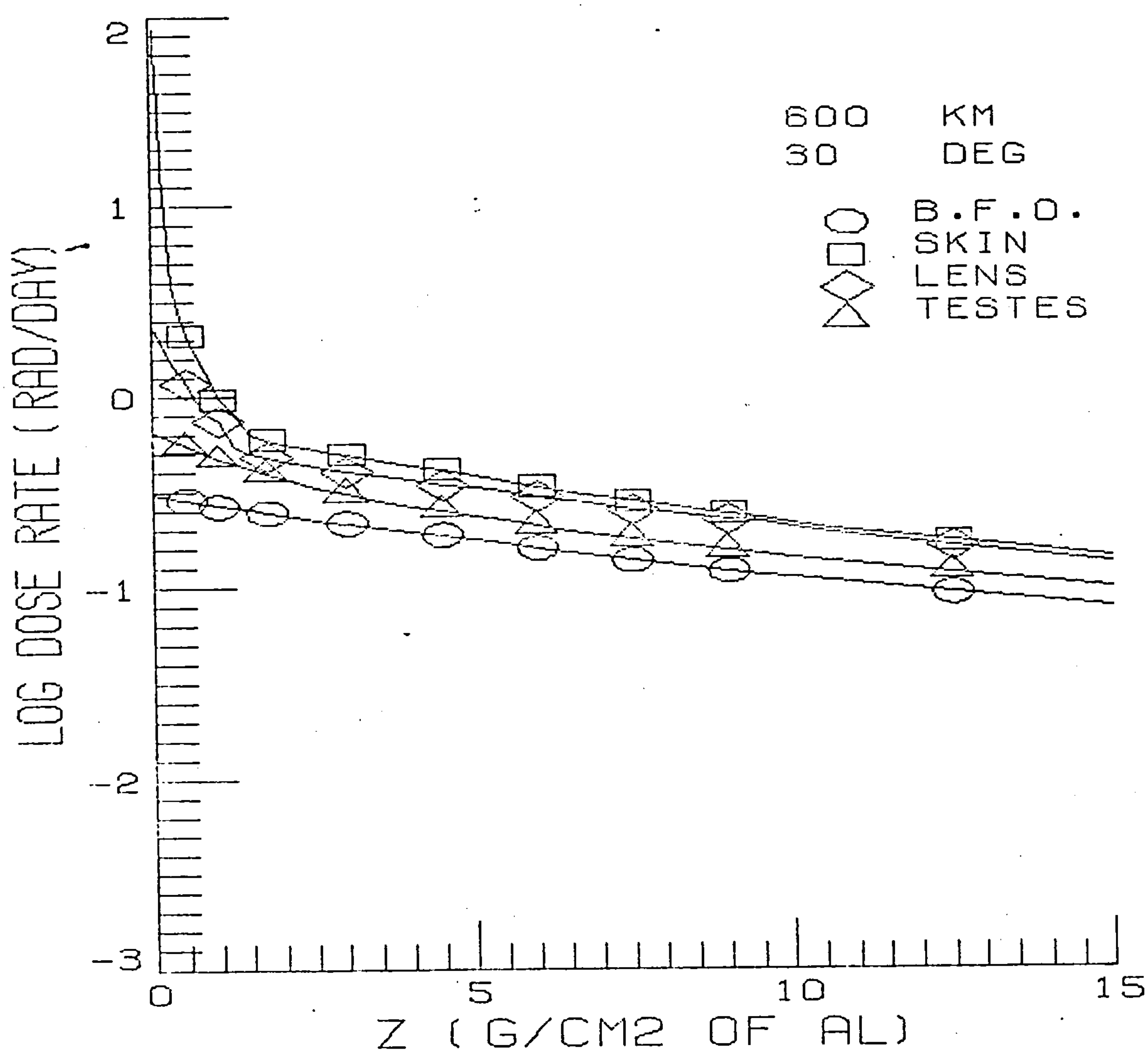

Figure 9.- Dose to critical body organs as a function of shield thickness for 30^0 inclined 600 km circular orbit.

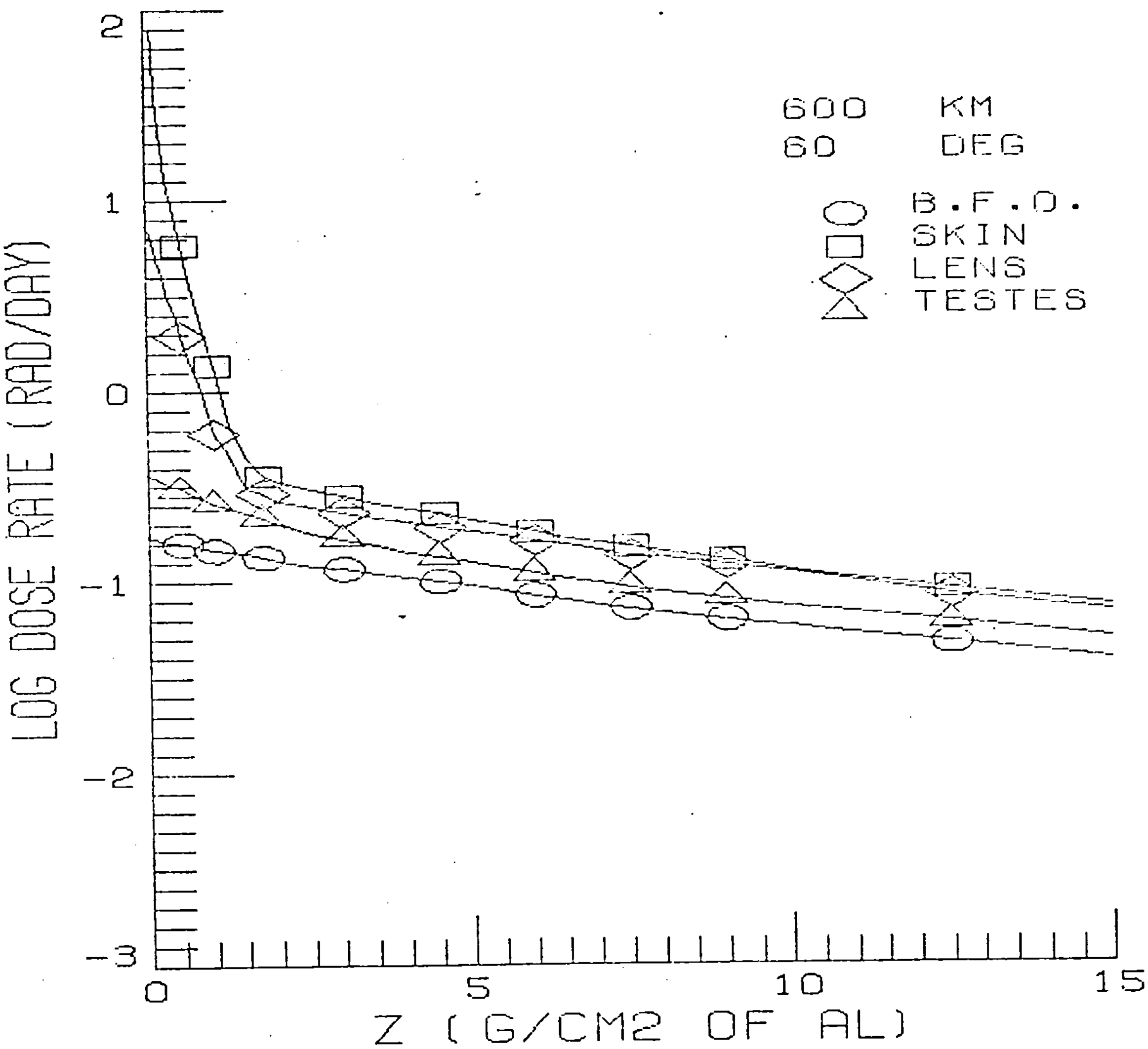

Figure 10.- Dose to critical body organs as a function of shield thickness for 60^{0} inclined 600 km circular orbit.

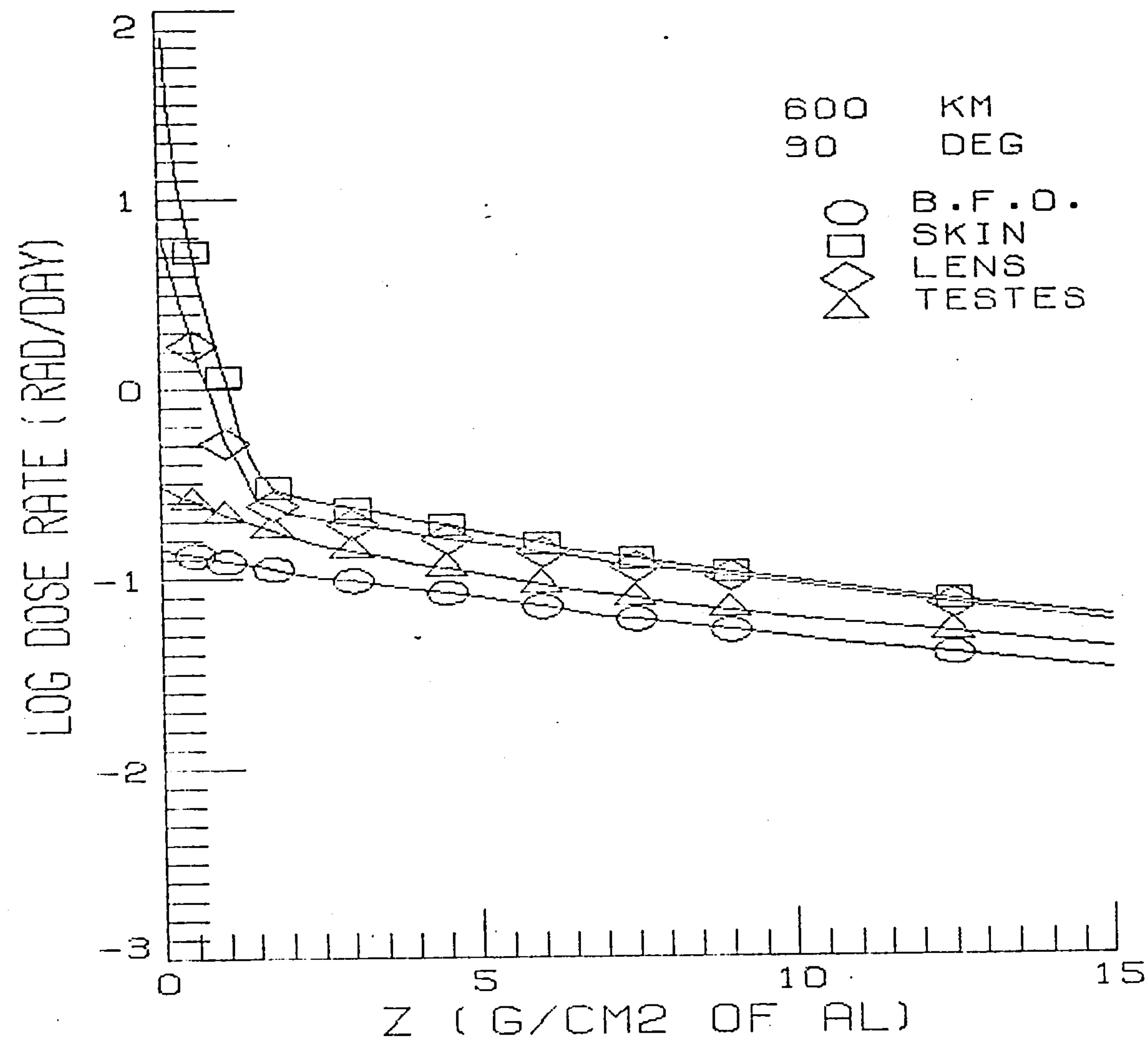

Figure 11.- Dose to critical body organs as a function of shield thickness for 90^0 inclined 600 km circular orbit.

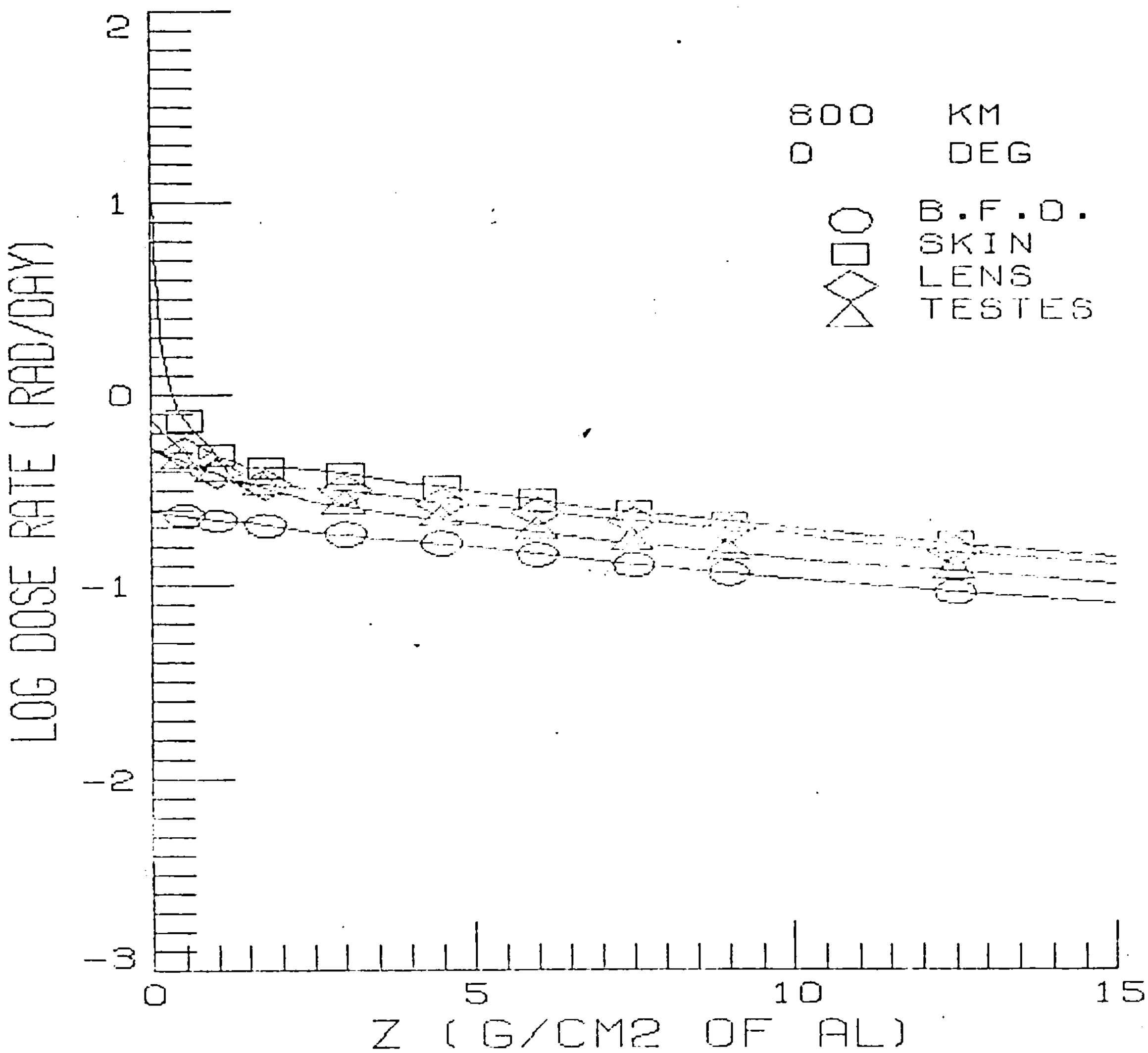

Figure 12.- Dose to critical body organs as a function of shield thickness for 0^{0} inclined 800 km circular orbit.

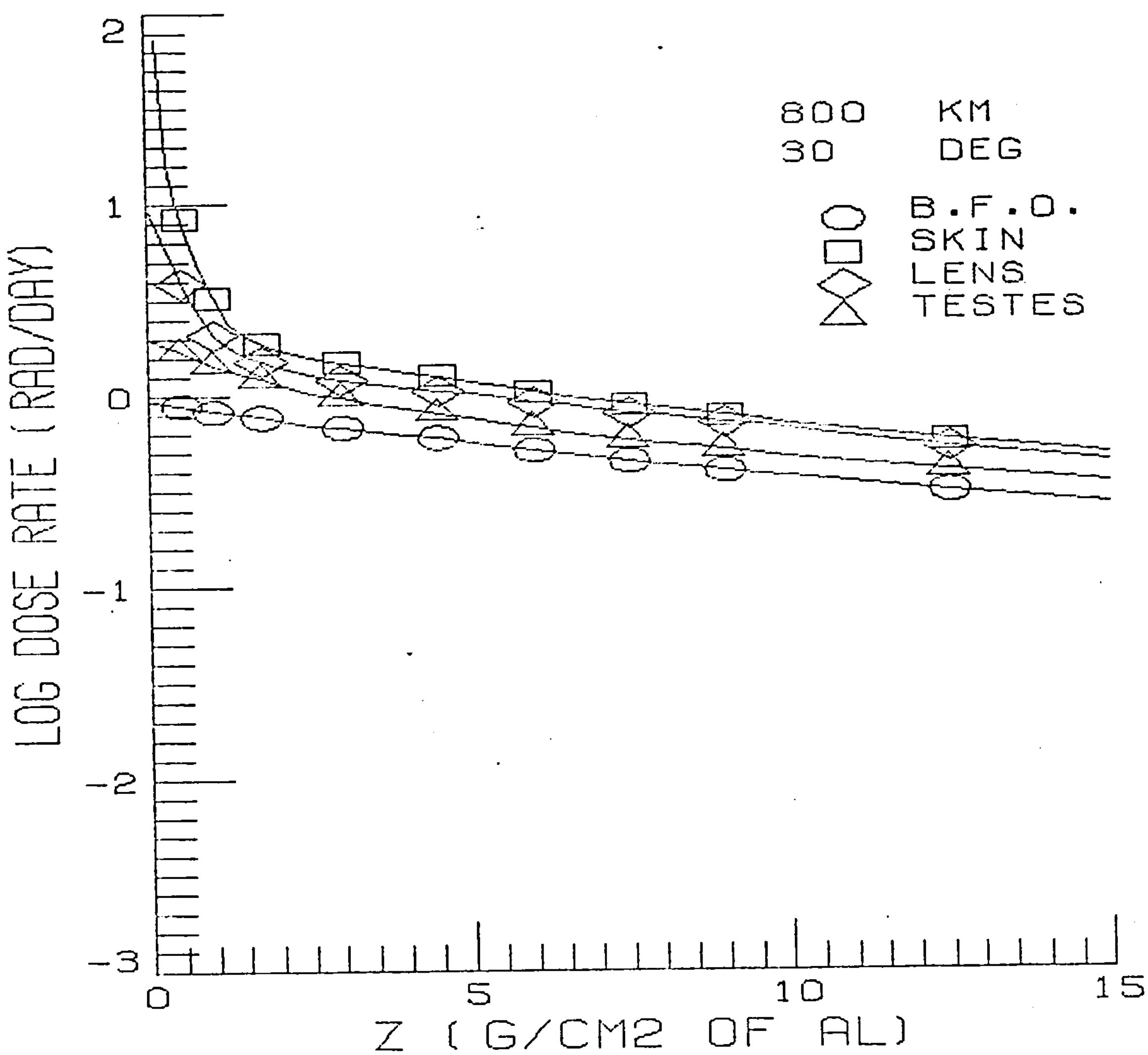

Figure 13.- Dose to critical body organs as a function of shield thickness for 30° inclined 800 km circular orbit.

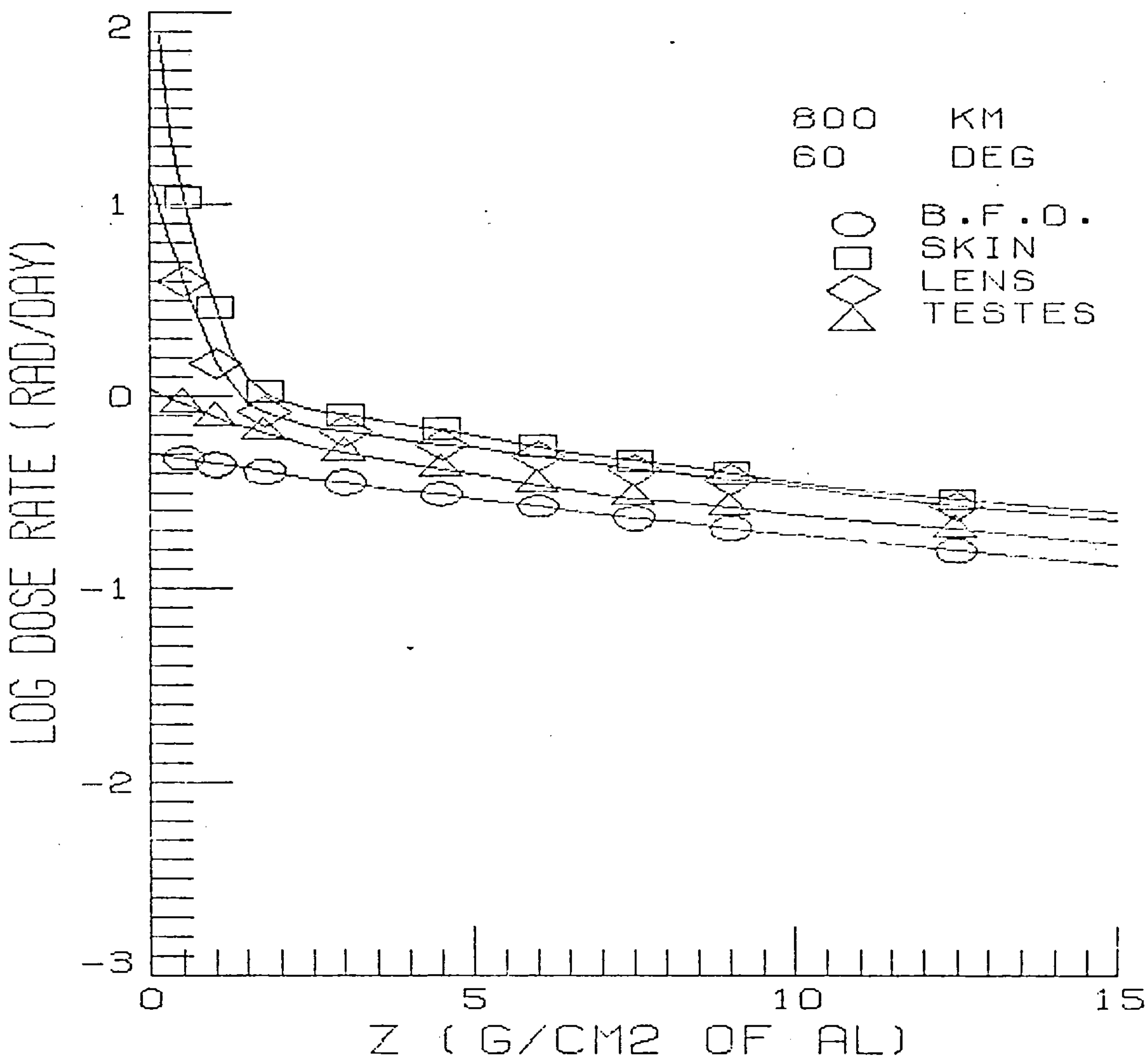

Figure 14.- Dose to critical body organs as a function of shield thickness for 60^0 inclined 800 km circular orbit.

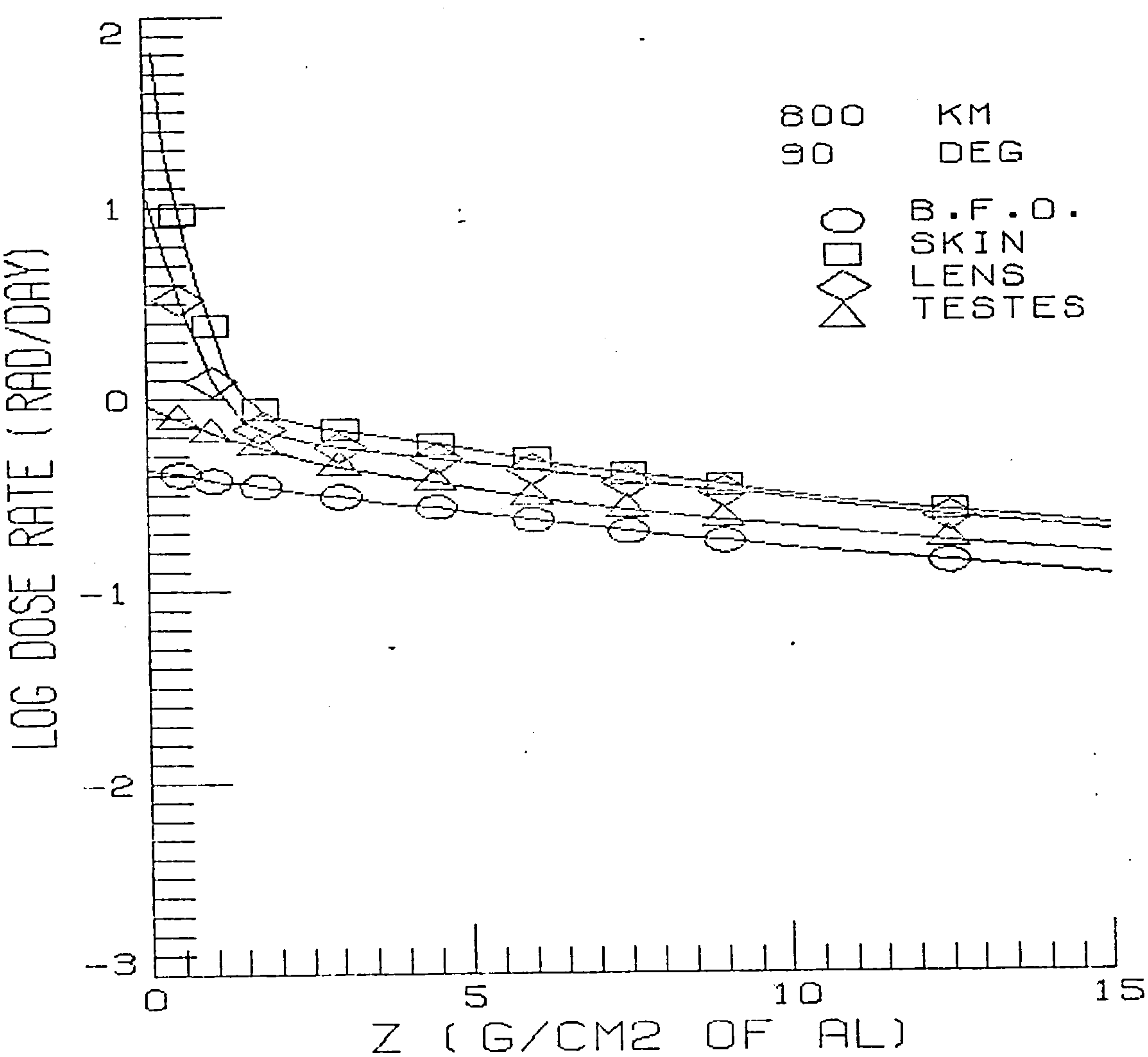

Figure 15.- Dose to critical body organs as a function of shield thickness for 90^{0} inclined 800 km circular orbit.

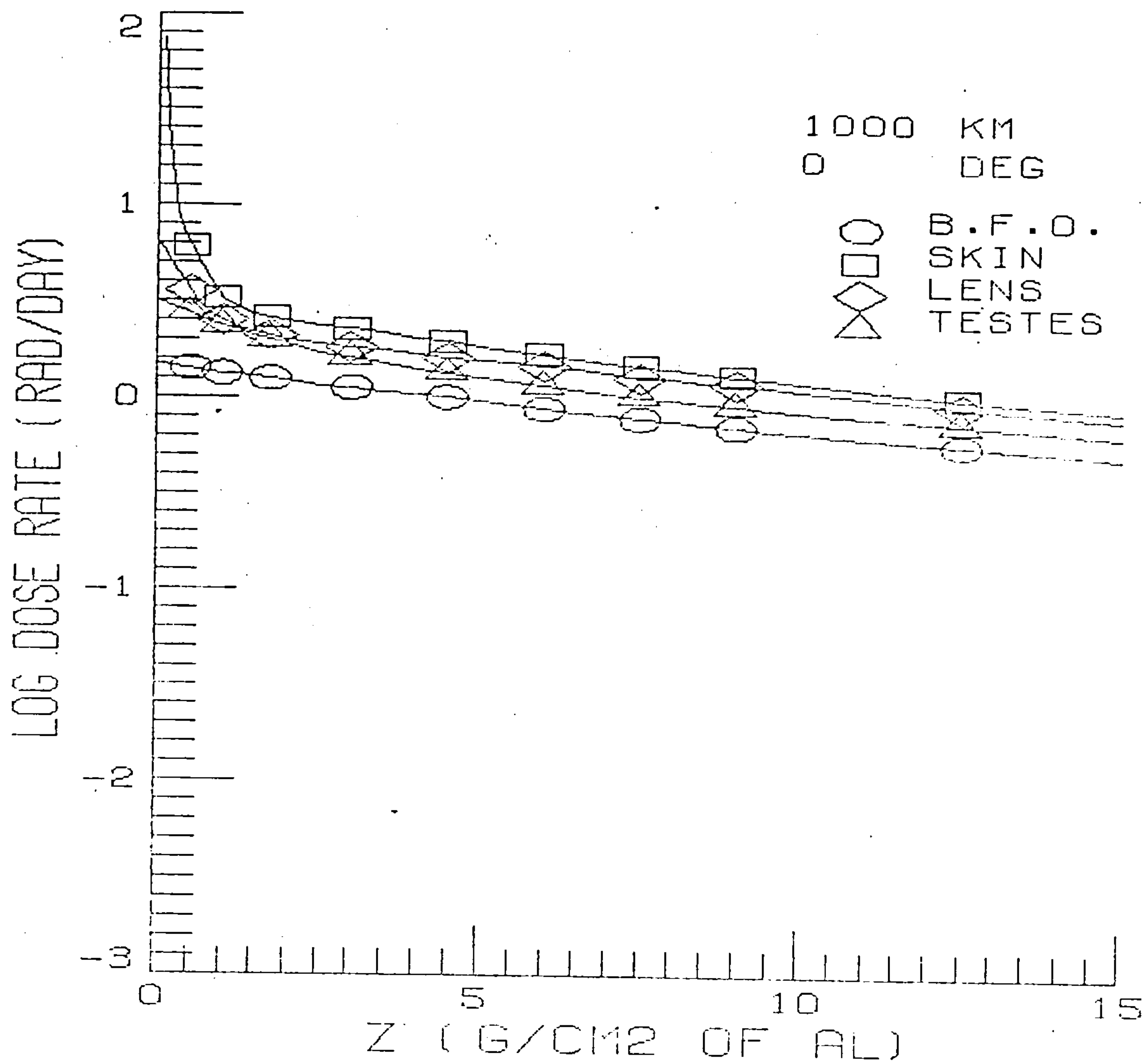

Figure 16.- Dose to critical body organs as a function of shield thickness for 0^0 inclined 1,000 km circular orbit.

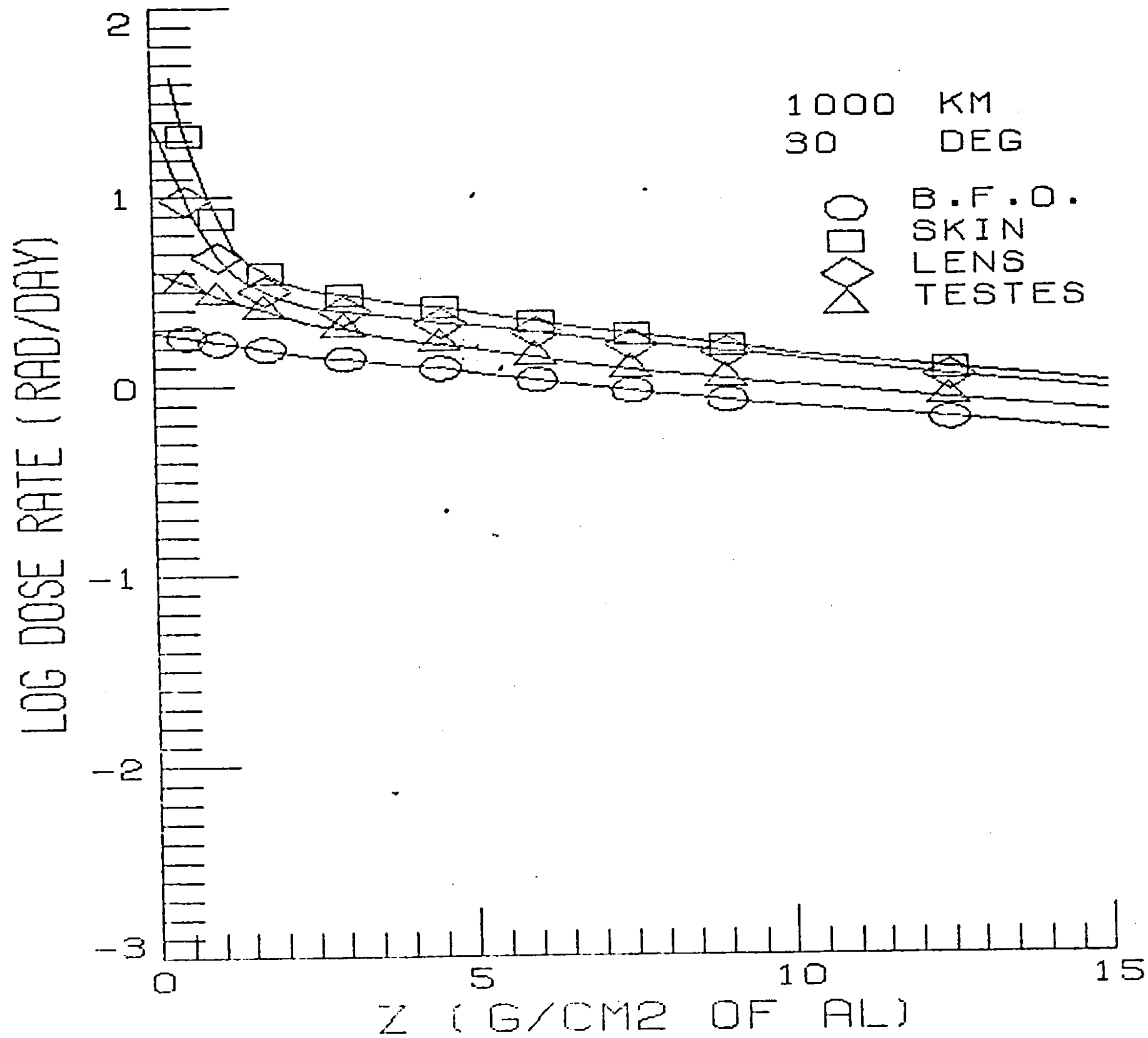

Figure 17.- Dose to critical body organs as a function of shield thickness for 30^{0} inclined 1,000 km circular orbit.

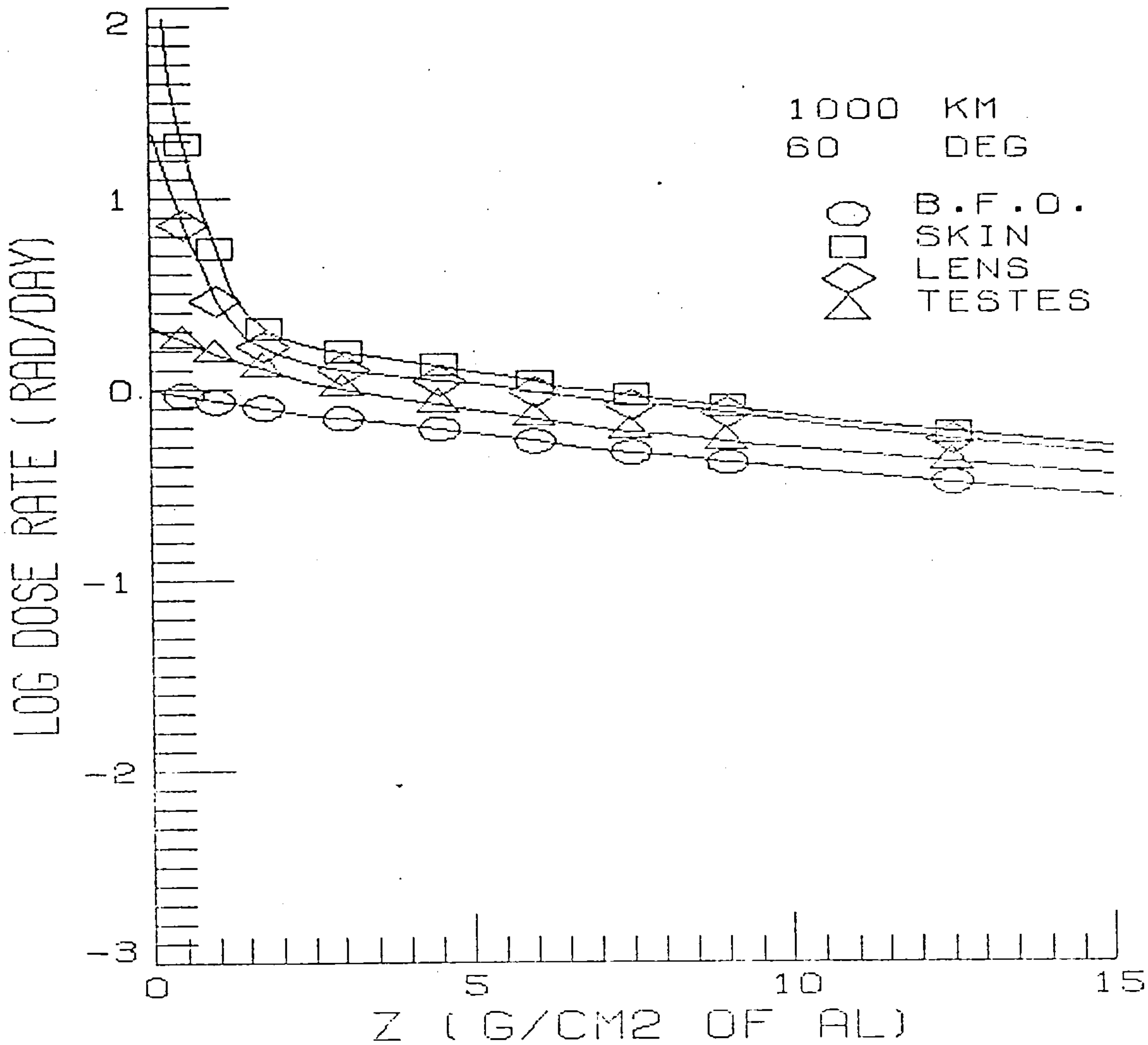

Figure 18.- Dose to critical body organs as a function of shield thickness for 60^{0} inclined 1,000 km circular orbit.

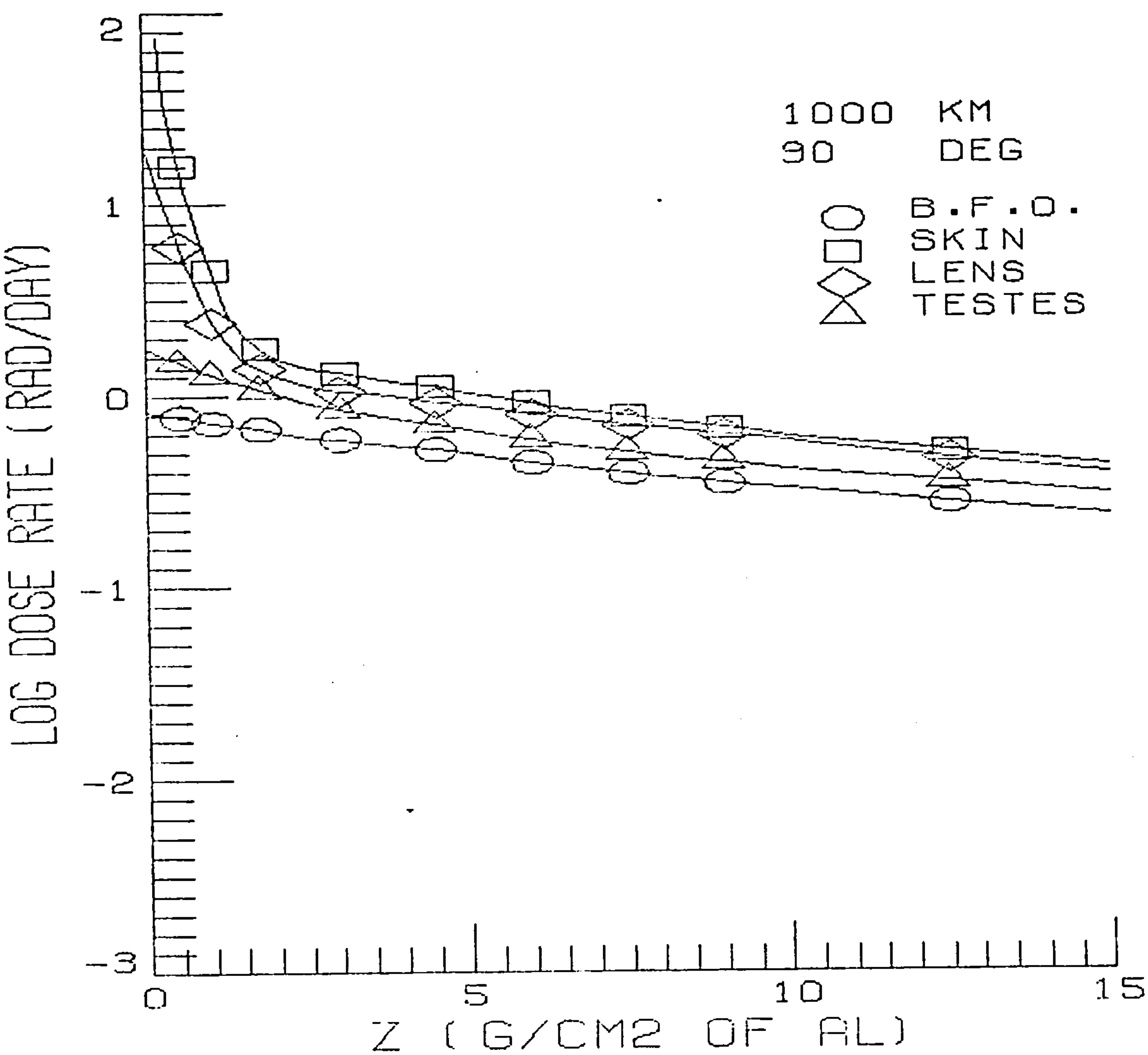

Figure 19.- Dose to critical body organs as a function of shield thickness for 90^0 inclined 1,000 km circular orbit.

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16. Abstract

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