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Human Exposure 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 thicknesses. 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 on the basis of presently accepted allowable exposure limits. A brief discussion is given concerning the anticipated impact of an ongoing reassessment of allowable exposure limits.

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. The purpose of the present report is 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. A detailed study of the impact of exposure limitation is needed if exposure limits are approached during the mission planning stage.

RADIATION EXPOSURE CONSTRAINTS

Radiation exposure constraints have been established on the basis of relative tissue sensitivities and scale of hurt (ref. 1). The rate of induction of solid tumors was assumed equal to the rate of induction of leukemia, and the doubling dose was 400 rems (ref. 2). The derived exposure constraints for bone marrow (blood forming organ (BFO)), skin, ocular lens, and testes 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 are 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 (QF) are available only for energetic protons after a 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 $QF \approx 1.5$ for radiations in LEO, which appear unnecessarily conservative compared with $QF \approx 1.3$ 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. Approximate 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 of Al with 80 percent of all directions having more than 7.5 g/cm^2 of Al. In contrast, Skylab had minimum thickness due to windows of 0.5 g/cm^2 of Al and 75 percent of the shielding on the order of 1 g/cm^2 of 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, the work of Billings and Langley (ref. 13) is used in which a simple spherical shell model of critical body organs is 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 with the minimum-number proton dosimeters (table 3 of ref. 13) generally shows reasonable estimation of dose except for skin and testes. The skin dose from electrons during EVA is in large error for the parameters of table 3 of reference 13. Skin dose estimates are made herein by an approximation to the minimum-error parameters (table 2 of ref. 13). Consequently, the skin dose is approximated by a dosimeter radius

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

where coefficient

$$C(z) = a + be^{-\alpha z} \qquad (2)$$

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, and α used in the present calculations.

ENVIRONMENTAL DATA

In the present calculations, the radiations other than those trapped in the magnetic field of the Earth 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 mrads/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. An evaluation of the heavy ion hazard will be made as soon as an adequate understanding is developed of their biological limits and shielding methods.

The trapped particle fluence is taken from a compilation of data (ref. 15) derived from the AE4 and AE5 electron models and AP5, AP6, and 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 is given in table 3. The electron data of Stassinopoulos (ref. 15) at 30°, in particular, are nearly an order of magnitude greater than the data at 28.5° and 35° of Watts and Wright (ref. 16). The origin of these differences is not known to the present authors and the data of reference 15 are taken 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 by using the SHIELDOSE program of Seltzer from the National Bureau of Standards (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 and equation (2) for the specific body organ, $D_{sphere}(z)$ is the dose in the center of an aluminum sphere of radius z, r_{organ} is 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 figures 1 through 5. Further results for the several shield thicknesses in table 4 are shown in table 5. An approximate meaning (place of occurrence) is associated with the thicknesses shown in table 4 as noted.

The results of table 5 are shown as graphs in figures 6 through 9. It is seen from figure 6(b) that skin dose for EVA at 500 km and 30° inclinations amounts to about 3.4 rads/day. If the maximum time in EVA per astronaut is 6 hours/day or 0.9 rad/day for EVA activity, the equivalent of 81 rads is received in the 90-day period of space activity. Hence, only 24 rads of additional skin exposure is allowable even though an additional 0.5 rad/day is received within an 1.0 g/cm^2 habitat during the remaining 18 hours of non-EVA status. Thus, the total dose received by the skin for an active EVA crew member is as much as 126 rads in 90 days or approximately the amount allowed by present guidelines assuming QF = 1 (table 1). If QF = 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 as a result of recent data on solid tumor induction (ref. 3).

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 but being mindful of future reductions on the basis of more recent biological data. It is estimated that exposure limits may be reduced by up to a factor of 4 which would greatly impact LEO operations. 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. Users of the present results are to be mindful of the limitations of the human geometric models employed which introduce additional uncertainty in the present estimates. One may only assume that when anticipated doses are low (10 percent of exposure limits or less), no significant impact of trapped radiation exposure on mission objectives is expected. However, if anticipated doses are 50 percent or more of the allowable exposure limits, then a detailed assessment of the impact of the radiation environment is required. In this respect, time variations in exposure rates are expected to be of vital importance during EVA operations as a means of reducing exposure.

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

Constraint	Ancillary reference risks				
	Primary reference risk, rems at 5 cm	Bone marrow, rems at 5 cm	Skin, rems at 0.1 mm	Ocular lens, rems at 3 mm	Testes, rems 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	.641	.428	.57
Lens	.5	.599	-.206	.25
Skin[a]	z/4	.720	-.356	.493

[a]$r < 2$ g/cm^2.

TABLE 3.- COMPARISON OF ENVIRONMENTS FOR INCLINATIONS OF 28.5° AND 35° WITH THAT FOR INCLINATION OF 30°

[Data for inclinations of 28.5° and 35° from Watts and Wright (ref. 16); data for inclination of 30° from Stassinopoulos (ref. 15)]

Energy, MeV	Proton fluence, protons/cm²-day, for altitude and inclination of -								
	200 km			400 km			800 km		
	28.5°	30°	35°	28.5°	30°	35°	28.5°	30°	35°
10	4.5E4	1.3E5	2.1E7	1.0E6	2.7E6	2.1E6	2.4E7	4.6E7	2.7E7
50	1.5E4	2.7E4	3.8E4	5.3E5	1.3E6	9.8E5	1.1E7	1.8E7	1.1E7
100	5.4E3	9.7E3	1.2E4	2.7E5	6.5E5	4.9E5	6.8E6	1.1E7	7.0E6

Energy, MeV	Electron fluence, electrons/cm²-day, for altitude and inclination of -								
	200 km			400 km			800 km		
	28.5°	30°	35°	28.5°	30°	35°	28.5°	30°	35°
1	1.7E3	1.1E4	3.3E3	4.5E5	1.8E7	4.8E6	7.3E7	5.8E7	1.0E8
2	5.5E2	6.2E3	7.4E2	7.8E4	5.2E6	8.4E5	1.2E7	1.5E8	1.7E7
3	2.5E2	2.1E3	3.7E2	8.6E3	6.7E5	6.3E4	9.9E5	1.9E7	1.3E6

TABLE 4.- RELEVANT VALUES OF SHIELD THICKNESS

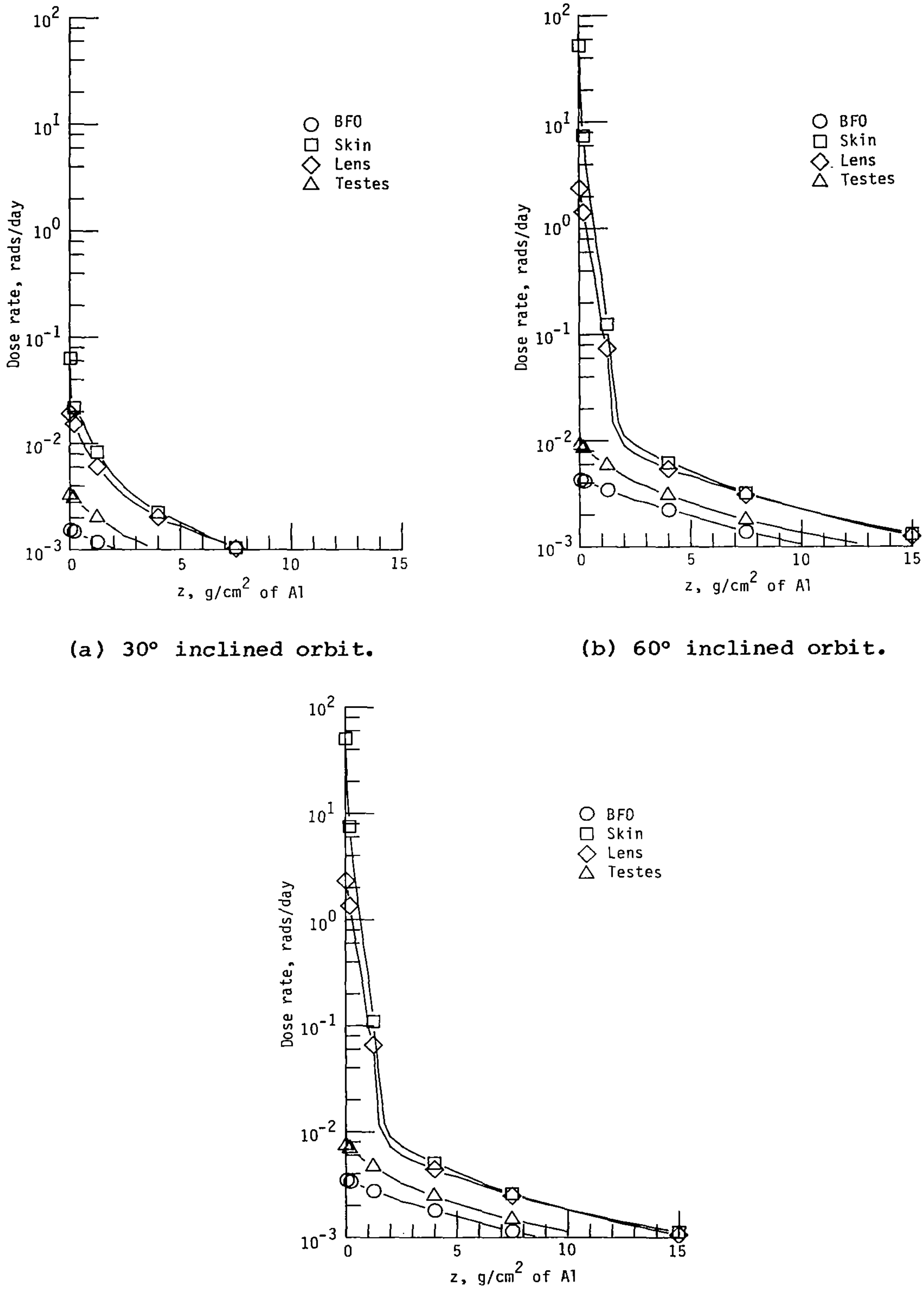
z, g/cm² of Al	Place of occurrence
0.2	Spacesuit
1.0	Space helmet, Skylab wall
2.0	Heavily shielded habitat
5.0	Heavily shielded vehicle, solar cosmic ray shelter

TABLE 5.- DOSE TO CRITICAL BODY ORGANS

Shield thickness, g/cm^2 of Al	Altitude, km	Dose, mrads/day, to -			
		BFO	Skin	Lens	Testes
0° inclined orbits					
0.2	200	0	0	0	0
	400	3	2	2	5
	600	8	26	16	17
	800	242	1 528	629	493
	1000	1455	16 513	5 040	2965
1.0	200	0	0	0	0
	400	3	2	2	5
	600	8	15	13	13
	800	219	483	393	386
	1000	1330	3 241	2 535	2339
2.0	200	0	0	0	0
	400	3	3	2	5
	600	7	13	11	11
	800	200	413	333	309
	1000	1219	2 487	2 008	1889
5.0	200	0	0	0	0
	400	3	4	3	4
	600	6	11	9	8
	800	157	311	266	208
	1000	973	1 883	1 597	1291
30° inclined orbits					
0.2	200	1	22	15	3
	400	71	1 278	334	146
	600	299	8 668	1 728	610
	800	921	39 829	6 623	1876
	1000	1871	111 004	16 838	3811
1.0	200	1	10	7	2
	400	62	222	170	110
	600	267	977	738	470
	800	828	3 296	2 088	1456
	1000	1682	7 760	4 741	2959
2.0	200	1	5	4	2
	400	54	146	117	84
	600	239	560	452	370
	800	746	1 732	1 398	1156
	1000	1516	3 568	2 881	2349
5.0	200	1	2	2	1
	400	38	90	79	50
	600	178	381	830	236
	800	568	1 178	1 014	754
	1000	1158	2 394	2 060	1536

TABLE 5.- Concluded

Shield thickness, g/cm^2 of Al	Altitude, km	Dose, mrads/day, to -			
		BFO	Skin	Lens	Testes
60° inclined orbits					
0.2	200	4	7 409	1 422	9
	400	50	13 382	2 529	102
	600	166	23 564	4 384	339
	800	494	47 428	8 253	1007
	1000	965	87 764	14 579	1965
1.0	200	4	361	117	6
	400	43	714	283	76
	600	147	1 355	608	258
	800	442	2 927	1 491	778
	1000	865	5 461	2 903	1522
2.0	200	3	11	9	5
	400	37	110	89	58
	600	130	329	266	202
	800	396	952	768	613
	1000	777	1 865	1 505	1204
5.0	200	2	5	5	3
	400	25	63	56	34
	600	95	210	184	125
	800	297	630	545	394
	1000	589	1 232	1 063	781
90° inclined orbits					
0.2	200	3	7 498	1 349	7
	400	41	12 956	1 326	84
	600	138	21 874	3 873	282
	800	418	40 826	6 990	853
	1000	810	74 542	12 157	1650
1.0	200	3	325	102	5
	400	36	625	242	63
	600	122	1 153	510	215
	800	375	2 419	1 230	660
	1000	727	4 497	2 400	1278
2.0	200	2	9	7	4
	400	31	90	73	48
	600	108	274	221	168
	800	336	798	644	521
	1000	653	1 559	1 259	1021
5.0	200	2	4	4	2
	400	21	52	46	28
	600	79	175	153	104
	800	254	534	461	337
	1000	496	1 053	893	658

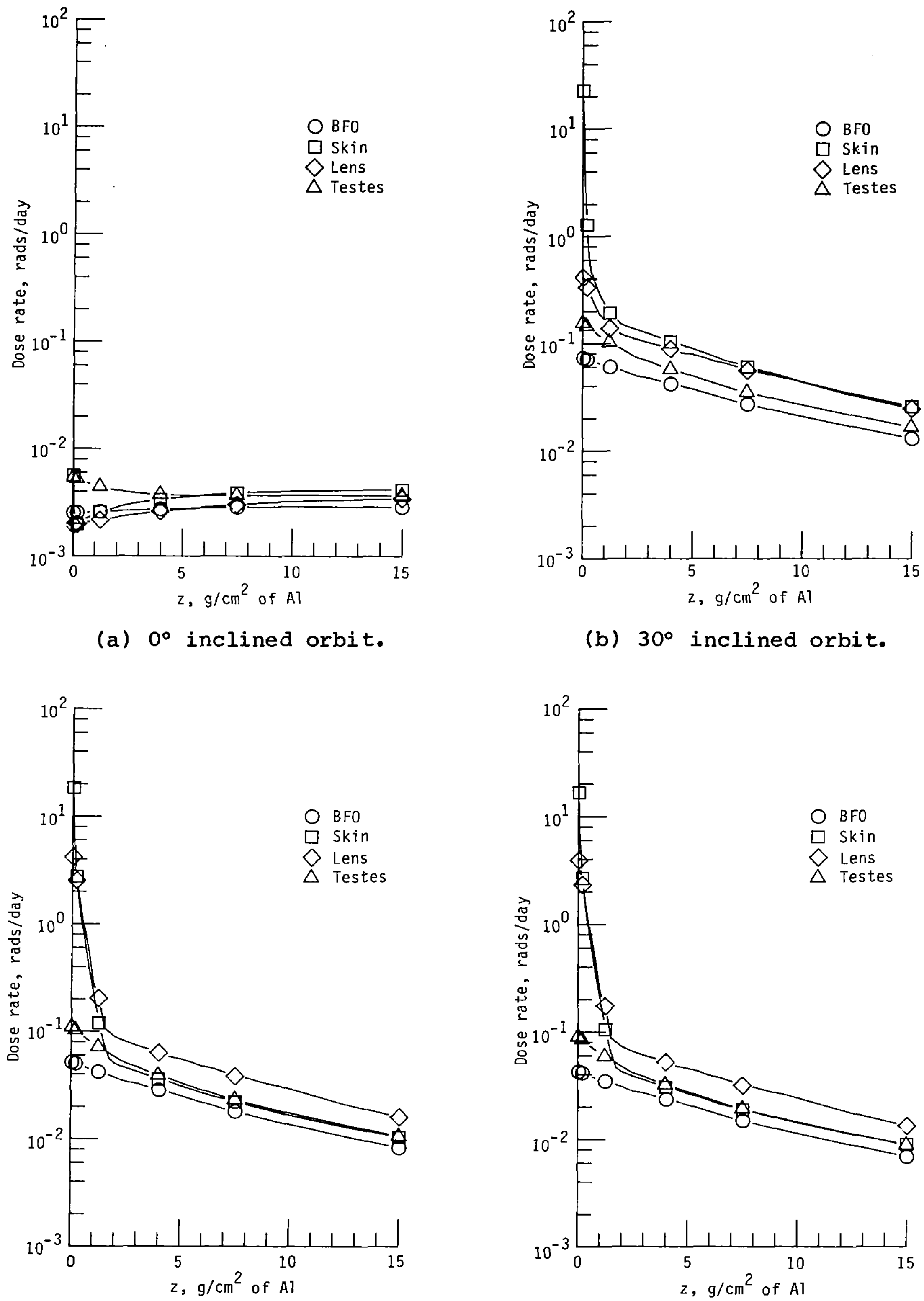


(a) 30° inclined orbit.

(b) 60° inclined orbit.

(c) 90° inclined orbit.

Figure 1.- Dose to critical body organs as function of shield thickness for 200-km circular orbits.



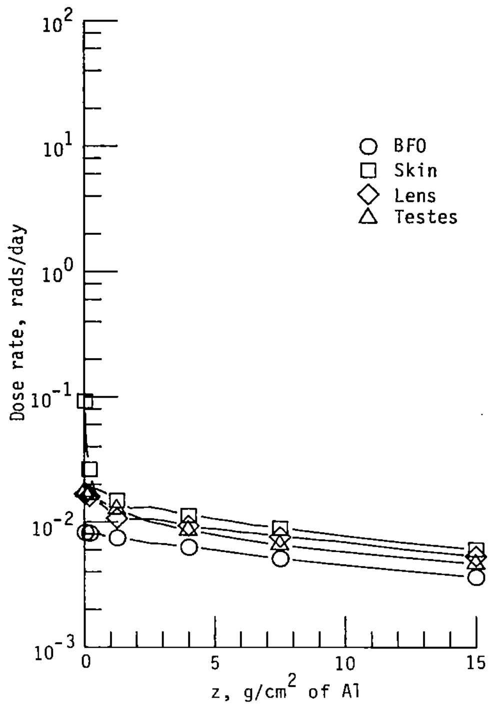
(a) 0° inclined orbit.

(b) 30° inclined orbit.

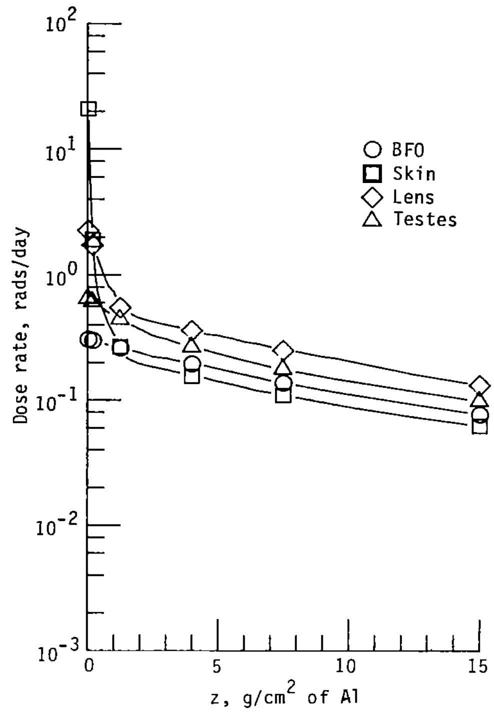
(c) 60° inclined orbit.

(d) 90° inclined orbit.

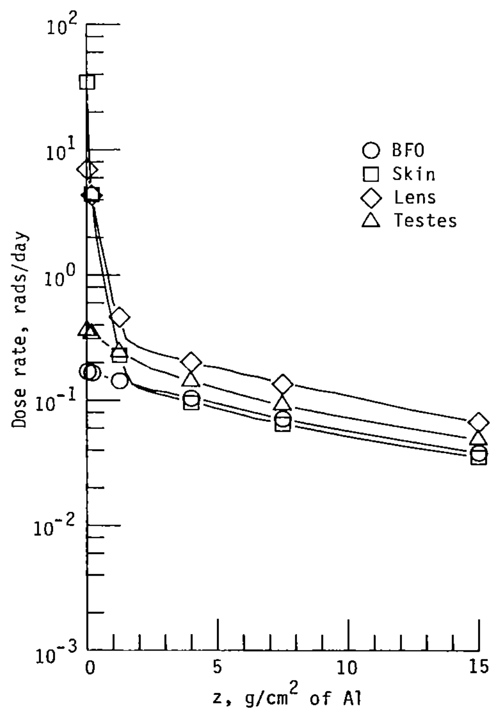
Figure 2.- Dose to critical body organs as function of shield thickness for 400-km circular orbits.



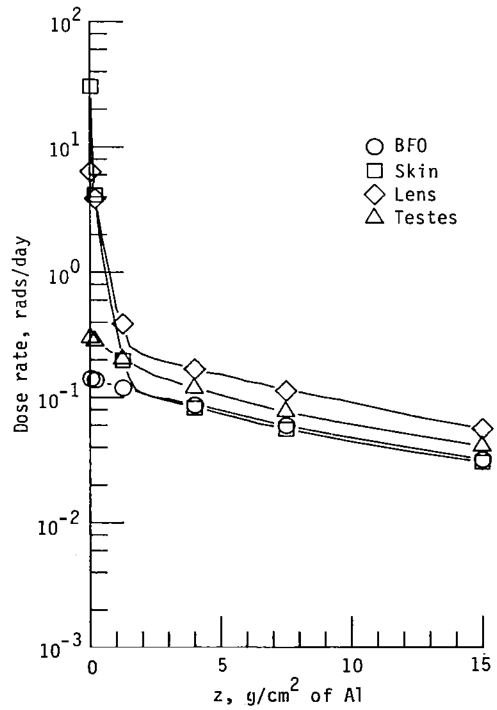
(a) 0° inclined orbit.



(b) 30° inclined orbit.

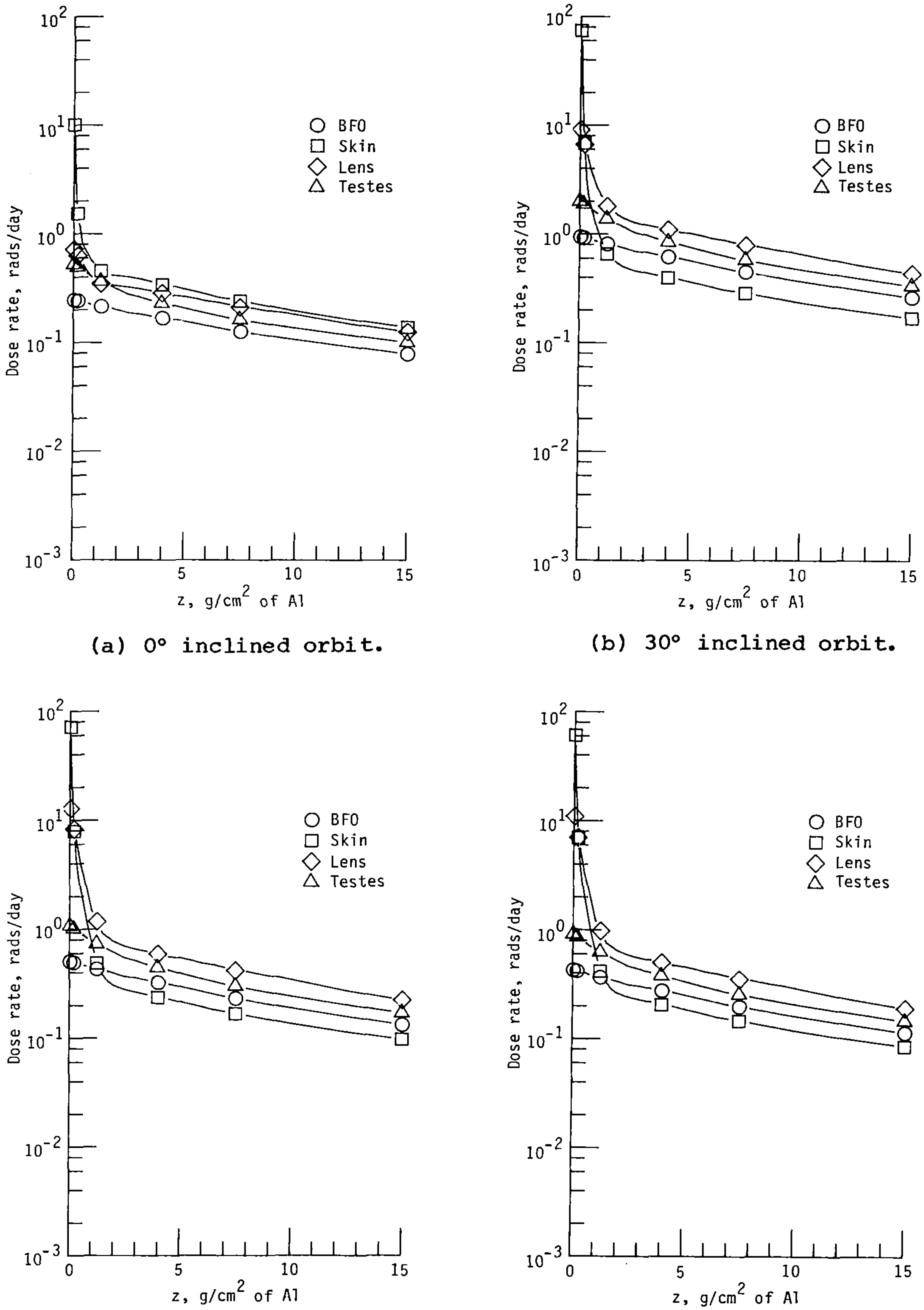


(c) 60° inclined orbit.



(d) 90° inclined orbit.

Figure 3.- Dose to critical body organs as function of shield thickness for 600-km circular orbits.



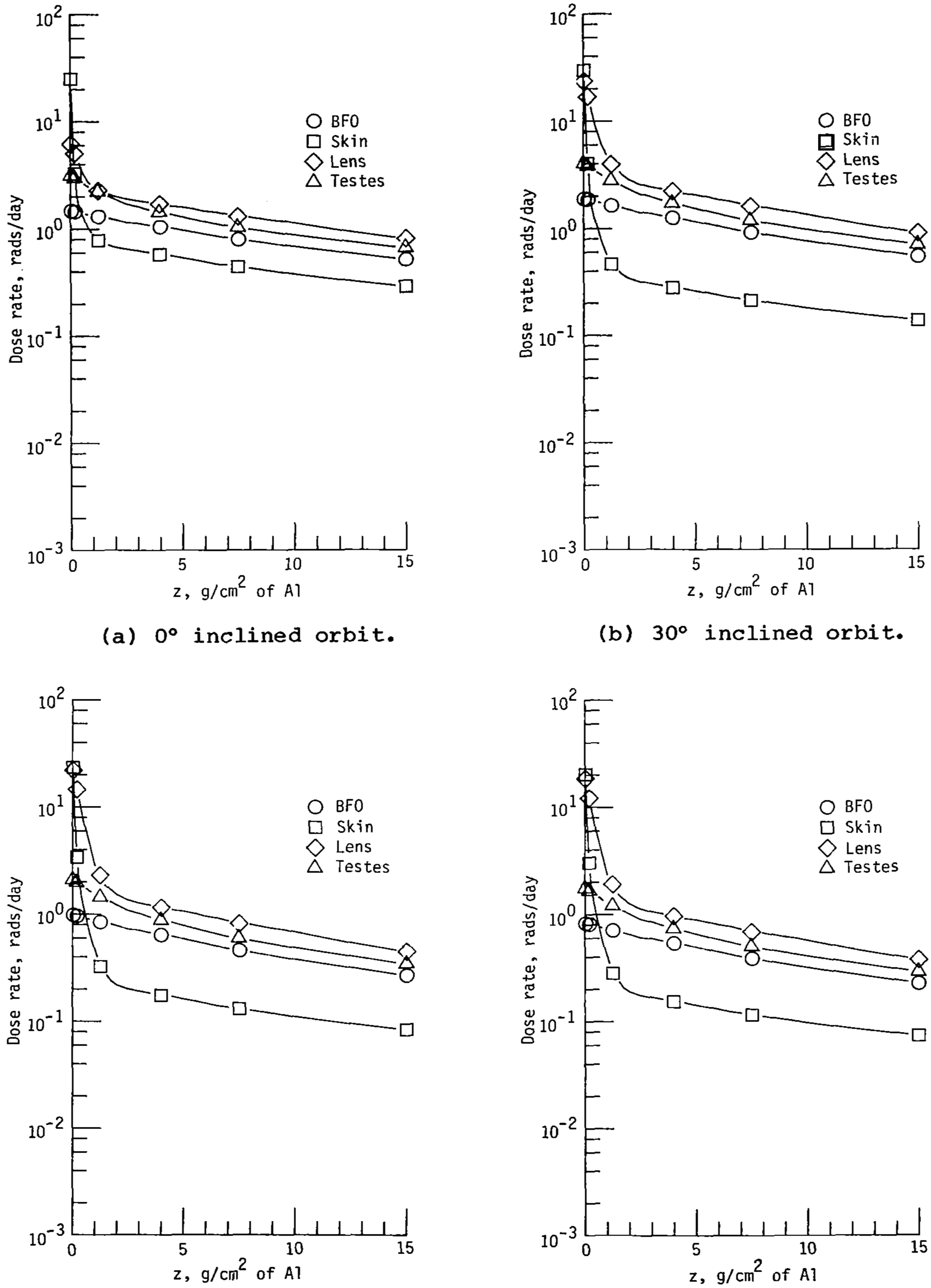
(a) 0° inclined orbit.

(b) 30° inclined orbit.

(c) 60° inclined orbit.

(d) 90° inclined orbit.

Figure 4.- Dose to critical body organs as function of shield thickness for 800-km circular orbits.



(a) 0° inclined orbit.

(b) 30° inclined orbit.

(c) 60° inclined orbit.

(d) 90° inclined orbit.

Figure 5.- Dose to critical body organs as function of shield thickness for 1000-km circular orbits.

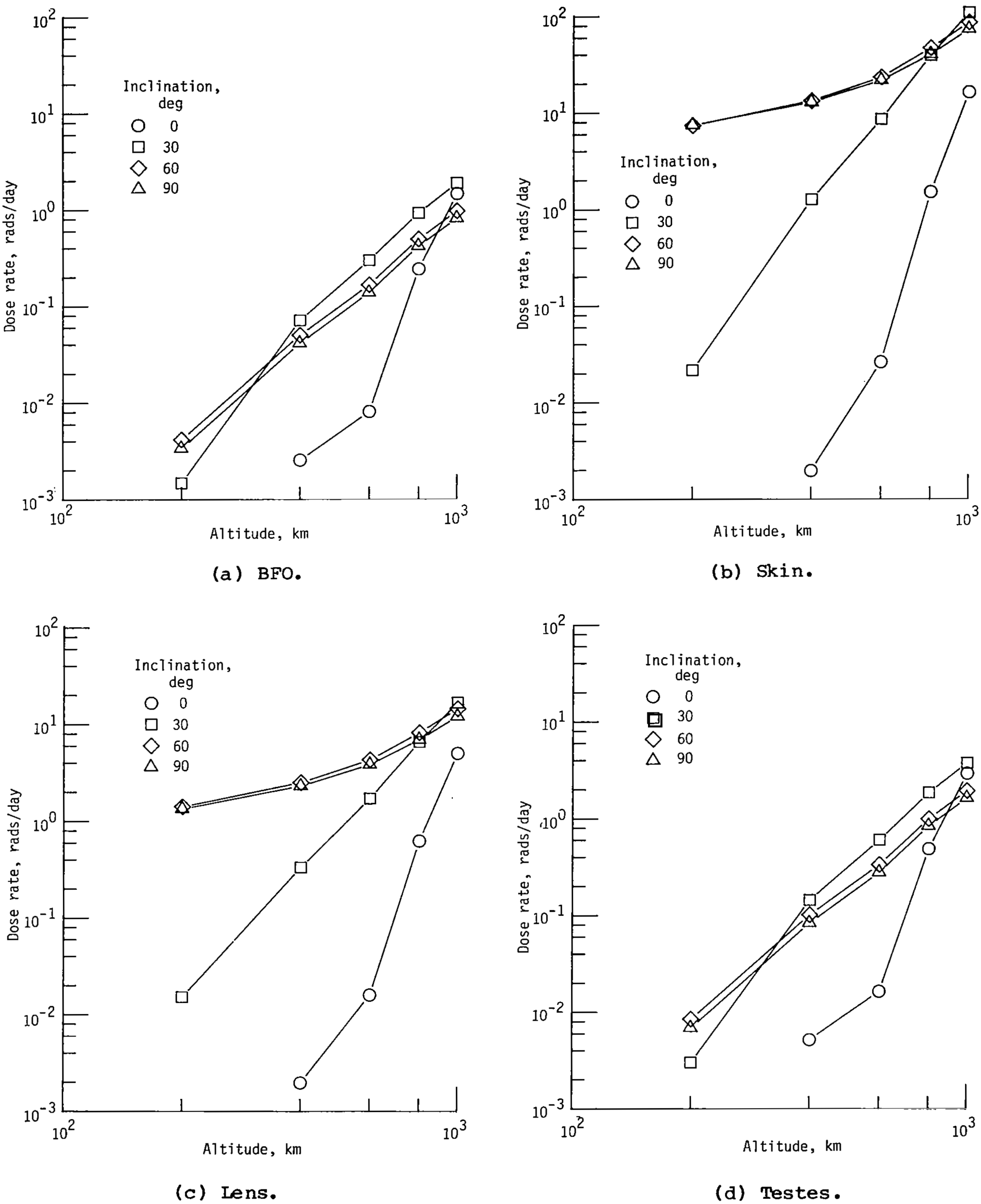
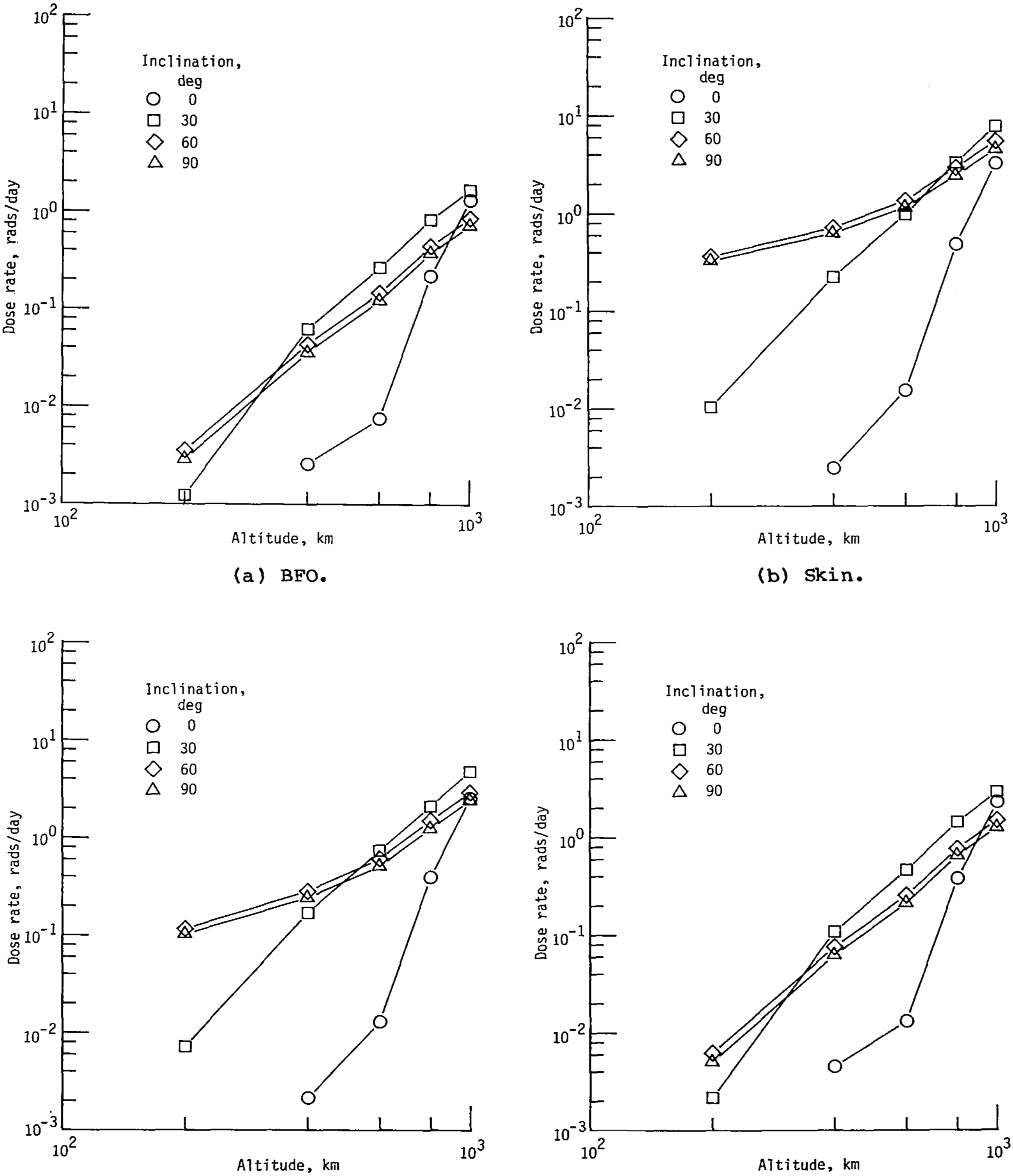


Figure 6.- Dose to critical body organs within shield of 0.2 g/cm^2 of aluminum.



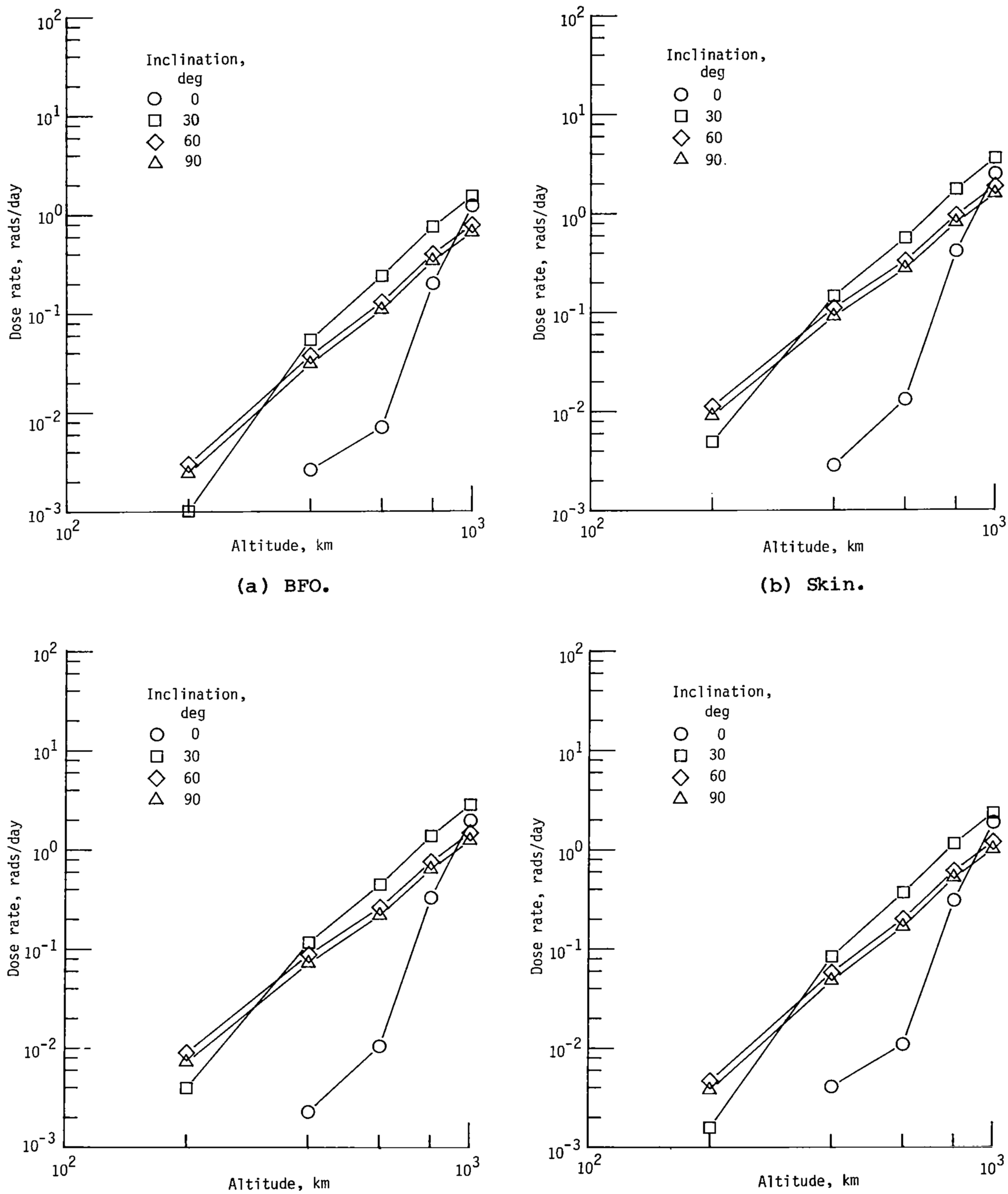
(a) BFO.

(b) Skin.

(c) Lens.

(d) Testes.

Figure 7.- Dose to critical body organs within shield of 1 g/cm^2 of aluminum.



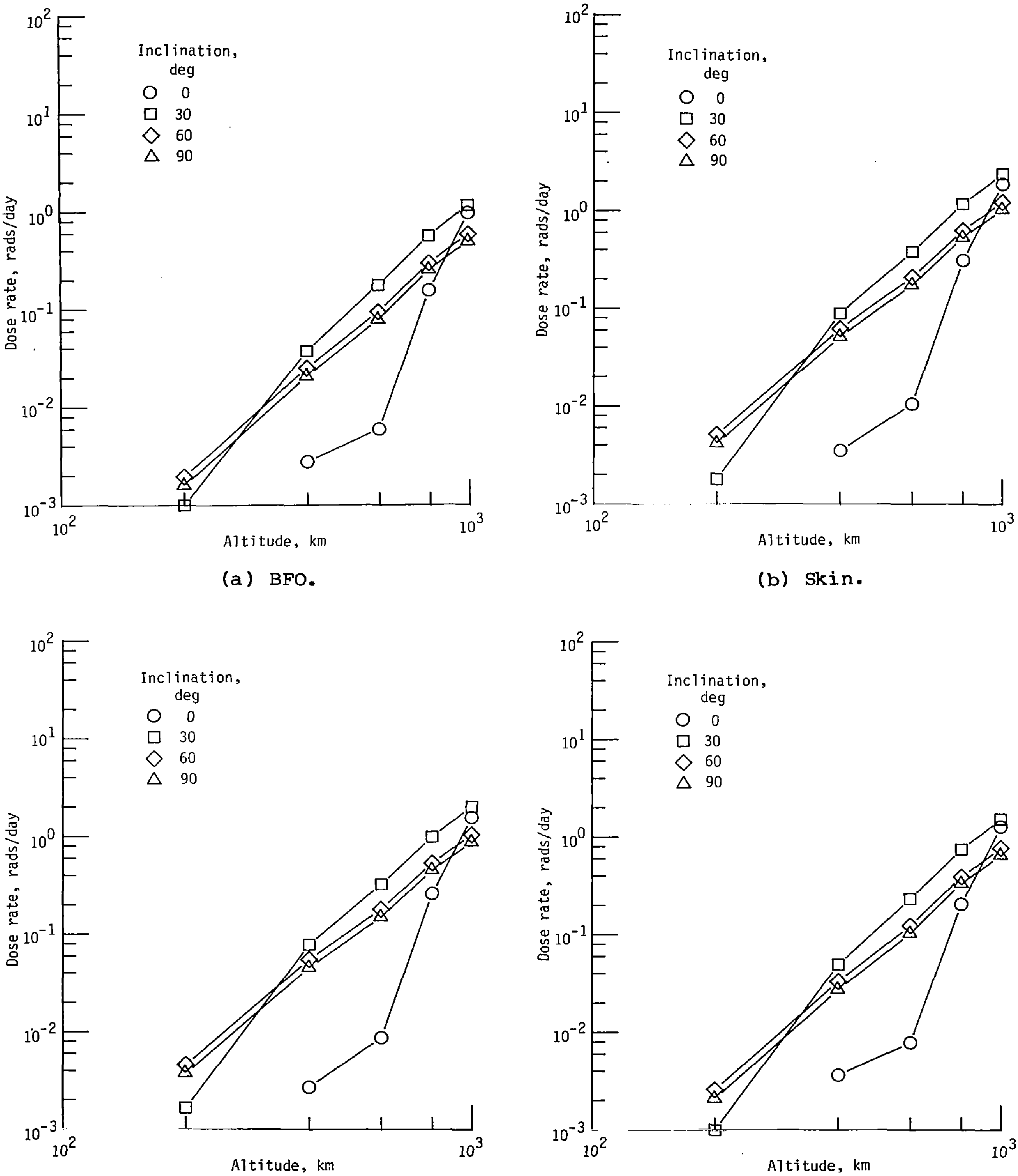
(a) BFO.

(b) Skin.

(c) Lens.

(d) Testes.

Figure 8.- Dose to critical body organs within shield of 2 g/cm^2 of aluminum.



(a) BFO.

(b) Skin.

(c) Lens.

(d) Testes.

Figure 9.- Dose to critical body organs within shield of 5 g/cm^2 of aluminum.

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16. Abstract

Human exposure to trapped electrons and protons 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. Detailed shielding studies should be performed before final design considerations. A sample impact assessment is discussed on the basis of presently accepted allowable exposure limits. A brief discussion is given on the anticipated impact of an ongoing reassessment of allowable exposure limits.

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