CONF-8710285--1

Presented at NATO Advanced Study Institute on "Terrestrial Space Radiation and its Effects," Corfu, Greece, October 12-23, 1987.
Plenum Publishing Corporation.

RADIATION PROTECTION GUIDELINES FOR SPACE MISSIONS

R. J. M. Fry

Biology Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

MASTER

CONF-8710285--1

DE88 006181

Research sponsored by the Office of Health and Environmental Research, U. S. Department of Energy, under contract DE-AC05-840R21400 with the Martin Marietta Energy Systems, Inc.

RADIATION PROTECTION GUIDELINES FOR SPACE MISSIONS

R. J. M. Fry

Biology Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

INTRODUCTION

The human presence in space has a short history but a long future. It is the nature of man to explore, to extend his boundaries and colonize new worlds. The environment beyond the radiation belts that shield the blessed earth is not as benign as our terrestrial environment. When every space mission was a new adventure risk from radiation did not loom large compared to the dangers involved in hurtling into space. Now despite the tragic setbacks, space travel is becoming routine and cosmonauts are spending increasingly long times in space.

The original recommendations for radiation protection guidelines were made by the National Academy of Sciences in 1970. Since that time the U.S. crews have become more diverse in their makeup and much has been learned about both radiation-induced cancer and other late effects. While far from adequate there is now some understanding of the risks that high-Z and -energy (HZE) particles pose. For these reasons it was time to reconsider the radiation protection guidelines for space workers. This task was undertaken recently by National Council on Radiation Protection (NCRP). The NCRP Scientific Committee 75 (NCRP SC-75) consisted of J. D. Boice, V. P. Bond, S. Curtis, R. J. M. Fry (Chairman), D. Grahn, W. K. Sinclair, J. B. Storer, P. Todd, D. S. Nachtwey (ex officio); Advisors: E. V. Benton and B. Worgul; Consultants: E. J. Ainsworth, E. L. Alpen, J. T. Lett, E. G. Stassinopoulos and C. A. Tobias.

Radiation Environments

Several authors have dealt with the characteristics of the radiation environments in this volume (see Benton, McCormick, Stassinopoulos) and the reader will find detailed descriptions in the chapters by those authors.

In low earth orbits (LEO) four factors determine the radiation exposure; altitude, orbital inclination, duration of the mission and shielding. In terms of radiation protection for LEO missions the radiation environment is made up of protons and galactic cosmic rays. In missions beyond the magnetosphere galactic cosmic rays predominate and

they consist primarily of protons with a small number of helium and heavier ions. The major concern in extended missions in deep space is the occurrence of a major, or so-called anomalously large, solar particle event (Kent, 1982). In these events the dose rate of the proton radiation may rise rapidly and to levels that are lethal if shielding is inadequate.

It is essential to have information about the spectra of the linear energy transfer (LET) and energies of the different radiations in the various space environments in order to estimate risks. Estimates of risks of late radiation effects, especially cancer, are required for missions in LEO. Whereas, for missions beyond the magnetosphere it is necessary to estimate the risks of both acute and late effects.

Radiation Protection

The aim of terrestrial radiation protection standards is to prevent the so-called nonstochastic effects such as cataract, and to limit cancer and genetic effects to a level that is considered acceptable.

In order to prevent nonstochastic effects it is necessary to know, with reasonable accuracy, the threshold doses for the different lesions of concern. In the case of x and gamma rays such limits can be set with acceptable confidence. However, the relative biological effectiveness (RBE) of neither protons nor heavy ions is known adequately. Similarly, the RBEs for cancer induction in humans by these radiations are not known.

The experimental data indicate that the RBE for proton-induced nonstochastic effects is about 1 to 1.3 (Clapp et al., 1974, Urano et al., 1984). However, the effects on only a few tissues have been studied.

In the case of stochastic effects not only are the estimates of risk in some doubt but there is also the problem of selecting a level of risk that is considered acceptable.

Cancer is the most important stochastic effect but there are no risk estimates for cancer induction in humans by protons or heavy ions. Therefore, we have to derive Quality Factors (Q) from the very sparse information from experimental animal studies in order to calculate dose equivalents for the different radiation qualities. The most pertinent data for protons come from a study on monkeys specifically designed to determine the acute and late effects of protons of the energies that would be encountered in space. This study was started in 1964 by Dalrymple and his colleagues (Dalrymple and Lindsay, 1966), and is still in progress at the USAF School of Aerospace Medicine at Brooks Air Force Base in Texas. A full account of the design of the experiment, exposure conditions and early results can be found in a collection of articles in Radiation Research, Vol. 28, 1966. The results, based on observations of 301 irradiated monkeys and 57 age-matched controls over a 20 year period, have been reported recently (Wood et al., 1986a). A number of dose levels of six proton energies plus 2 electron and x ray groups were studied, thus, the number of animals per cell is inconveniently small. Despite the multiplicity of experimental groups there are interesting findings. First, brain tumors account for a higher fraction of the total cancer mortality than expected (Wood et al., 1986b). It is possible that

exposure conditions contributed to the high incidence of brain tumors. However, it is becoming clear that irradiation of the head in children carries a considerable risk of induction of brain tumors (Ron et al., 1988). Secondly, the doubling dose for fatal cancers in the monkeys from exposure to 55 MeV protons is about 2.5 Gy. Thirdly, based on pooled data for the high-energy proton and x-ray groups, which were used as a low-LET reference radiation, the RBE of 55 MeV protons for cancer mortality appears to be about 1.5.

In the recent report on "The Quality Factor in Radiation Protection" (ICRU, 1986), a Q value of 25 was suggested for protons and heavier ions. The evidence in support of the selection of such a value is not presented in detail. In space the spectrum of proton energies is extremely broad and the RBEs on which the Q values can be based must be dependent on the LET of the specific proton energies. While heavy ions of iron may be the most important heavy ion biologically, a number of other ions of different LETs are encountered in space. Therefore, some average Q must be derived for the composite proton and heavy ion radiations that constitute the galactic cosmic rays. Curtis (1986) has described the approach used by NCRP SC-75 to obtain an average Q for exposures experienced in different types of missions. The average Q is defined simply as the ratio of the dose equivalent to the absorbed dose in the organ of interest. The derivation of the average Q is dependent on knowing or calculating the differential energy spectrum of the particles in the body. The LET_{∞} to Q relationship reported by ICRP (1977) was used to derive the Q of particles of specific energy.

The average Q used for calculating the dose equivalents for low earth orbits (LEO), geosynchronous orbit (GEO) and a lunar mission are shown in Table 1.

Table 1 (from Curtis 1986)

Mission	Inclination (o)	Altitude (km)	Shielding (g/cm^2)	Average Q
LEO	28	450	1	1.1
LEO	57	450	1	1.3
LEO	90	450	1	1.3
GEO		∿36,000	2	1.1
Lunar			4	2.9 (Galactic cosmic rays)

The question of Q values for high-LET radiations is under consideration by the various International and National bodies and it is likely that some further changes in the recommendations for Q value will be made in the future. However, the values shown in Table 1 for LEO and GEO are in reasonable agreement with the few RBE values that can be derived from the data reported (Clapp et al., 1974; Urano et al., 1984; Tatsuzaki et al., 1987). The RBE's for the induction of skin cancer by

protons of some energies appear to be higher than for most nonstochastic effects (Burns et al., 1978).

In the case of heavy ions it is not clear what relationship of energy deposition to RBE is appropriate. The particle tracks of heavy ions are complex and the higher Z particles traverse more than one cell. Iron is considered the most important of the heavy ions in deep space and RBE values are shown in Table 2.

Table 2. RBE Values for ^{56}Fe (600 MeV/n and 190 keV/μm)

Test System	Endpoint	RBE	References
Mouse CFU-s	D_{10}	2.2	Ainsworth et al. (1985)
Mouse Testes	D_o	1.5	Alpen & Powers-Risius (1981)
Lens of the eye	Opacities		
Rabbit		∿5	Lett et al. (1986a)
Mouse		5-20	Worgul (1986)
Mouse	Life Span	<1.0	Ainsworth (1986)
Mouse: C3H	Malignant		
10T 1/2 cells	Transformation	∿3	Yang et al. (1985)
Mouse: Harderian Gland	Tumors	∿30	Fry et al. (1985)

The relationship of RBE to LET has been determined for cell killing and mutation in human cells (Cox et al., 1977). The RBE rises steeply above about 20 keV/μm reaches a peak at 100-200 keV/μm and then declines as steeply as it rose. This relationship of RBE to LET is similar for effects in tissues that reflect cell killing (Fig. 1). In the case of tumors there are data only for Harderian gland tumors in mice exposed to a range of LETs. The RBE for tumorigenesis shows a similar pattern except the curve plateaus at about 30, and up to an estimated LET of 650 keV/μm for Argon-40 (570 Mev/n) does not decline. This suggests that the RBE-LET relationship for tumorigenesis may differ from that for other endpoints and certainly the RBE values appear higher (Fry et al., 1985). The RBEs for tumorigenesis were determined from the ratios of the slopes of the initial linear segments of the dose-response curves, for each of the heavy ions, and the slope of the response to the reference gamma radiation. In the case of iron-56 and argon-40 the initial slope is linear up to about 20 rad. Over this dose range, the number of cells being traversed by a particle is increasing with dose. Whereas, the RBEs for cell killing were determined from the exponential segments of the survival curves. The difference in the derivation of the RBEs may account for the difference in RBE-LET relationships and perhaps the RBE values.

Information about the acute effects of not only iron but of other HZE particles on cells and tissues has accumulated in the last few years. As noted above the RBE-LET relationship is similar to that for cell killing except that the plateau of the curve for T-1 cells extends to about 400 keV/μm.

A decision must be made about the correct basis of determining Q values for heavy ions and the selection of an average Q for the determination of dose equivalents.

HZE Particles

Despite the considerable number of studies at the tissue and cellular level (see reviews by Leith et al., 1983 and Blakely et al., 1984; Kiefer, 1985) much remains to be learned about the biological effects of HZE particles. Until more definitive data become available estimates of the risk that these particles pose for travel in deep space must remain tentative.

The potential for severe biological damage that may result in both acute and late effects has been noted and discussed for many years. Unfortunately, our understanding of the relationship of the biological effects to the complex pattern of energy deposition that occurs with HZE particles is little more than when the report of the National Academy of Sciences was published (NRC, 1973). For example, there are no data for genetic effects and in only one tumor system has a spectrum of ions, including iron, been studied (Fry et al., 1985).

Here in Greece it may be appropriate to compare the foreboding consequences predicted for exposure to HZE particles with Damocles's plight. Certainly the specter of damage to clusters of cells in vital centers in the CNS or the fovea of the retina has hung like a Damoclean sword over the head of long missions in deep space. The concept of the microlesion caused by HZE particles, as described in (NRC, 1973), was originally described in terms of the characteristics of the particles. The effect of HZE particles, it was suggested "was that of a microbullet that might destroy a column of cells, one cell width in diameter" (NRC, 1970a).

The validity of the concerns about microlesions induced by HZE particles (Todd, 1983), depends on whether the fluences experienced during space missions beyond the magnetosphere would ever be sufficient to deplete cells in critical centers to a critical level. If, as has been suggested, late breakdown of DNA in nondividing cells occurs (Lett et al., 1986b), then predictions of late effects based on data for acute effects may be invalid.

Single exposures to relatively high doses and fluences of heavy ions have not caused deaths in mice, or damage to the CNS that is sufficiently severe to cause clinical signs. In fact, Ainsworth (1986) has reported no greater life shortening after exposures to ^{56}Fe ions than after gamma rays. These experiments were carried out with higher fluences than are likely to be encountered in space.

Risk Estimates and Recommendations of Career Limits

Radiation has not been a factor in the safety of space missions in the past. Even in the Apollo missions the absorbed doses were relatively small. The main reason for the low absorbed doses is that the majority of the astronauts have been on missions of short durations. The longer missions such as Skylab and in particular Mir, have been in relatively benign radiation environments.

In the future more people will spend longer times in space. No longer is space the realm of a small number of seasoned pilots, like the original astronauts and cosmonauts. Women have joined the ranks and specialists from various disciplines are now crew members. The radiation risks may seem small compared to the dangers involved in leaving Earth and spaceflight itself, but space workers should not face later in life,

excessive risk of cancer induced by radiation exposure in space.

The most important late effect of radiation is cancer. Most, if not all, of radiation-induced life shortening can be attributed to excess cancer. Years ago the latest of late effects, namely genetic effects, was the effect about which there was greatest concern. Now, the lack of evidence of significant excess of genetic effects in the atomic bomb survivors has turned the concern to cancer.

The information about radiogenic cancer in man comes, in part, from the populations exposed to the radiation from the atomic bombs, industrially exposed populations such as uranium miners (NRC, 1988) and radium dial painters (Rowland and Lucas, 1984). An increasing amount of data are coming from the populations exposed, either from radiological diagnostic procedures or during radiotherapy for benign and malignant disease (Boice, 1988). Radiation provides a remarkable education about both the physical factors and the biological factors involved in carcinogenesis. Questions of importance in the understanding of human cancer can and have been answered in experimental animal experiments (Fry and Storer, 1987), and there are important aspects of concordance between human and experimental findings (Storer et al., 1988).

In Table 3 the many factors involved in radiogenic cancer are shown.

Table 3. Factors that influence radiation risk estimates

Radiation Characteristics	Biological Characteristics	Approach to Analysis
Dose	Age	Dose-response models
Dose rate	Sex	Projection models
Fractionation	Genetic background	Absolute risk
Radiation quality	Special features of the tissue or organ under study	Relative risk

The risk estimates that NCRP SC-75 has used are those derived by the National Institutes of Health (NIH) ad hoc committee on the development of radioepidemiological tables (NIH, 1985). In the derivation of probabilities of causation, the NIH committee took into account both age and sex as determinants of cancer risk. NCRP SC-75 has taken advantage of this stratification by setting separate career limits for males and females as a function of age at first exposure. Thus, eight career limits have been derived, ranging from 1.0 Sv (100 rem) to 4.0 Sv (400 rem), as shown in Table 4.

Table 4. Career limits (Sv) for radiation exposure of space station workers.

Lifetime Excess Risk of Fatal Cancer		Recommended career limits (Sv) Age (yr) at first exposure 25	35	45	55
3×10^{-2}	Male	1.50	2.50	3.25	4.00
3×10^{-2}	Female	1.00	1.75	2.50	3.00

Career limits have been based on a lifetime excess risk of cancer of 3×10^{-2}, which is comparable to the risks in occupations such as construction and agriculture but is greater than those for terrestrial radiation-exposed workers. The risks of space travel are considerable, and it will be important to estimate the total lifetime risk for workers on the space station. All things considered, a 3% lifetime excess risk of death from cancer seems reasonable, especially as most cancers occur late in life and cause less life shortening than do accidental deaths in many other occupations.

A simple relationship of career limits to the age at first exposure is shown in Fig. 2. The career dose equivalent is approximately 2.0 + 0.075 (age - 38)Sv for females and 2.0 + 0.075 (age-30)Sv for males, up to 4.0 Sv.

Terrestrial radiation protection standards are set in the hope of preventing nonstochastic effects. Career and shorter-duration limits for astronauts were chosen by NCRP SC-75 to protect critical tissues. The recommended limits for the bone marrow, lens of the eye and the skin are shown in Table 5. The new proposed limits should provide the desired protection and also some flexibility for planning missions.

Table 5. Dose equivalent limits (Sv).

	Bone Marrow	Ocular Lens	Skin
	Recommended dose-equivalent limits (Sv)		
Career	1.5	4.0	6.0
Annual	0.50	2.0	3.0
30 d	0.25	1.0	1.5

Table 6 shows the comparison of recommendations made in 1970 (NRC, 1970b), with the new proposed limits shown in Tables 4 and 5. The career limits for all endpoints have been reduced. The limits for shorter intervals than career are equal or slightly higher than those recommended previously. The changes are considered justified on the basis of new data and a better understanding of risks. The interested reader is

referred to Field and Upton (1985) for discussion of nonstochastic effects and to Sinclair (1986, 1987) for an account of risks and radiation protection.

Table 6. Recommended radiation exposure limits.

Constraints	Bone Marrow		Eye		Skin	
	NRC/NAS	NCRP	NRC/NAS	NCRP	NRC/NAS	NCRP
	Recommended dose equivalents (Sv)					
30 days	0.25	0.25	0.37	1.0	0.75	1.0
1 year	0.75	0.5	1.12	2.0	2.25	3.0
Career	4.0	1.0-4.0	6.0	4.0	12.0	6.0

The most important population for the derivation of estimates of cancer risk following whole-body irradiation are the atomic bomb survivors in Nagasaki and Hiroshima. The dosimetry for those populations have just been reassessed (Roesch, 1987) and much new mortality data is in the process of being analyzed.

The following may help to put the recent changes in perspective. The changes in the dosimetry include: 1) an increase of about 20% in the estimated yield of the Hiroshima bomb, 2) a reduction in the estimated doses from neutrons in both cities. The estimated neutron dose for Hiroshima is about 10% of the previous estimate. The neutron doses are now so small that direct estimates of neutron RBEs may be precluded or be much more difficult, and 3) there is little change in most of the gamma ray organ doses because various changes in the new estimates tend to cancel each other out. The new estimate of the attenuation of the free-in-air kerma by the walls of the homes is about twice that used in the previous dosimetry. But the transmission of gamma radiation to the deep organs such as bone marrow is significantly greater than earlier estimates. Probably, future risk estimates for radiogenic cancer will be somewhat higher mainly because of the increasing solid cancer mortality data. New risk estimates based on the information from all exposed populations should be available in 1988.

In fact, new risk estimates are being published but these still require further dosimetry and analysis. Tables 7 and 8, from the report of Radiation Effects Research Foundation at Hiroshima (Preston and Pierce, 1987), illustrate the trends suggested by the new dosimetry. These estimates are based on organ doses (work on organ dose estimates is still underway). It is important to recognize that many previous estimates from Japan, and some being used currently by some spokesmen, were based on kerma. For whole-body exposure to gamma rays, 1 rad (10 mGy)-kerma is equal to about 0.5 rad (5 mGy) and with fission neutron about 0.2 rad (2 mGy). It is the kerma doses that have shown the dramatic changes whereas organ doses (as yet) have altered little. It is organ doses that are important for risk estimates and protection standards. For risk estimates dose must be adjusted further for factors, such as radiation quality, to obtain dose equivalents (in rem or Sieverts).

The value of the RBE for neutrons that is assumed in the new dosimetry has an impact on how much the risk estimates are influenced by the new dosimetry. If an RBE of one is assumed the risk estimate for all cancer except leukemia, based on organ doses, is virtually unchanged by the dose reassessment (Table 7). But if an RBE of 20 is used the risk estimate for leukemia increases by over 130% (Table 9). It is ironic that the RBE of neutrons, the very concern that, indirectly, stimulated the reassessment of the dosimetry remains central to accurate estimation of risk in the study of the Japanese.

Table 7. All cancer except leukemia, intestinal dose: Estimates of excess relative risk averaged, with equal weights, over six categories of sex and age ATB. For each of these estimates the coefficient of variation is about 14%. (Preston and Pierce, 1987)

Dosimetry	Excess Relative Risk per Gray
T65D	0.72
T65D, DS86 subcohort	0.80
DS86	0.60
DS86 total kerma <4 Gy	0.70

Table 8. Leukemia, marrow dose: Estimates of average excess leukemia risk over the follow-up period averaged, with equal weights over six categories of sex and age ATB. For each of these estimates the coefficient of variation is about 14% (Preston and Pierce, 1987).

Dosimetry	Excess Risk 1950-85 per 10^4 person-year Gray
T65D	2.87
T65D, DS86 subcohort	3.52
DS86	3.23
DS86 total kerma <4 Gy	3.46

Table 9. Leukemia and nonleukemia, organ dose equivalent: Estimates of risk for selected values of the organ dose RBE (Preston and Pierce, 1987).

	Nonleukemia Excess Relative Risk Risk per Sievert			Leukemia Average Excess Risk per 10^4 person-year Sievert		
RBE	T65D	DS86	DS86 <4 Gy	T65D	DS86	DS86 <4 Gy
1	0.72	0.60	0.70	2.92	3.93	3.16
5	0.60	0.58	0.68	2.26	3.09	3.31
10	0.50	0.56	0.66	1.75	2.91	3.15
20	0.36	0.53	0.62	1.21	2.62	2.86
30	0.28	0.49	0.59	0.93	2.37	2.62

When there is a consensus about the best estimate of risk of radiation-induced cancer it will be necessary to reassess the recommendations for career limits for whole-body exposures in space made by NCRP SC-75.

Conclusions

Risks of radiation-induced effects in LEO missions can be estimated and radiation protection guidelines can be recommended with considerable confidence. This is the case because the effects of the radiation qualities, similar to those encountered in LEO, are reasonably well known. However, the RBE for protons and neutrons should be defined more precisely.

The estimates of risks in missions in deep space are another matter because of the lack of definitive information about the effects of HZE particles. Further measurements of the fluences and LET spectra of heavy ions beyond the magnetosphere will help the estimation of doses that could be incurred. Also, it is essential that the question of the dangers of microlesions be settled unequivocally.

REFERENCES

Ainsworth, E. J., Mahlmann, L. J., Prioleau, J. C.1985, Inactivation of mouse marrow stem cells by heavy charged particles, Lawrence Berkeley Laboratory Annual Report, LBL-20345, UC-48, p 128.

Ainsworth, E. J., 1986, Early and late mammalian response to heavy-charged particles, Adv. Space Res. 6(11):153.

Alpen, E. L. and Powers-Risius, P., 1981, The relative biological effects of high Z, high LET charged particles for spermatogonial killing, Radiat. Res. 88:132.

Alpen, E. L., Powers-Risius, P., and McDonald, M., 1980, Survival of intestinal crypt cells after exposure to high Z, high energy charged particles, Radiat. Res. 83: 677.

Blakely, E. A., Ngo, F. Q. H., Curtis, S. B., and Tobias, C. A., 1984, Heavy-ion radiobiology: Cellular studies, Adv. Radiat. Biol. 11:295.

Blakely, E., Personal communication.

Boice, J. D., 1987, Carcinogenesis - A synopsis of human experience with external exposure in medicine, J. Natl. Cancer Inst. 79:1295.

Burns, F. J., Strickland, P., Vanderlaan, M., and Albert, R. E., 1978, Rat skin tumor incidence following single and fractionated exposures to proton radiation, Radiat. Res. 74:152.

Clapp, N. K., Darden, E., Jr., and Jernigan, M. C., 1974, Relative effects of whole-body sublethal doses of 60 MeV protons and 300 kVp x rays on disease incidences in RF mice, Radiat. Res. 57:158.

Curtis, S. B., W. Atwell, R. Beever, and A. Hardy, 1986, Radiation environments and absorbed dose estimations on manned space missions, Adv. Space Res. 6(11):269.

Cox, R. J., Thacker, J., Goodhead, D. T. and Munson, R. J., 1977, Mutation and inactivation of mammalian cells by various ionizing radiation, Nature 267:425.

Dalrymple, G. V., and Lindsay, J. R., 1966, Protons and space travel - An introduction, Radiat. Res. 28:365.

Field, S. B. and Upton, A. C., 1985, Non-stochastic effects: Compatibility with present ICRP recommendations, Int. J. Radiat. Biol. 48:81.

Fry, R. J. M. and Storer, J. B., 1987, External radiation carcinogenesis, Adv. Radiat. Biol. 13:31.

Fry, R. J. M., Powers-Risius, P., Alpen, E. L., and Ainsworth, E. J., 1985, High-LET radiation carcinogenesis, Radiat. Res. 104:S188.

International Commission on Radiological Protection (ICRP), 1977, Recommendations of the ICRP Publication 26, Annals of the ICRP 1(3), Pergamon Press, Oxford, England.

International Commission on Radiation Units and Measurements (ICRU), 1986, Quality Factor in Radiation Protection, ICRU Report 40, ICRU, Bethesda, MD.

Kiefer, J., 1985, Effects of very heavy ions, Int. J. Radiat. Biol., 48:873.

Leith, J. T., Ainsworth, E. J., and Alpen, E. L., 1983, Heavy-ion radiobiology: Normal tissue studies, Adv. Radiat. Biol. 10:191.

Lett, J. T., Cox, A. B., and Lee, A. C., 1986a, Cataractogenic potential of ionizing radiations, in: Animal Models that Simulate Man, Adv. Space Res. 6(11):295.

Lett, J. T., Cox, A. B., and Bergtold, D. S., 1986b, Cellular and tissue responses to heavy ions: basic considerations, Rad. Environ. Biophys. 25:1.

National Research Council (NRC), 1970a, Report of a Study Convened by the Space Science Board, National Academy of Sciences, p. 44, Washington, DC.

National Research Council (NRC), 1970b, Radiobiological Advisory Panel, Committee on Space Medicine, Space Sciences Board, Radiation Protection Constraints Guide for Space - Mission and Vehicle - Design Studies Involving Nuclear Systems, National Academy Press, Washington, DC.

National Research Council (NRC), 1973, Radiobiological Advisory Panel, Committee on Space Biology and Medicine. Space Science Board, National Research Council. HZE-Particle Effects in Manned Spaceflights, D. Grahn, ed., National Academy Press, Washington, DC.

National Research Council (NRC), 1988, Committee on the Biological Effects of Ionizing Radiation (BEIR IV), Health risks of radon and other internally deposited alpha-particle emitters, National Academy Press, Washington, DC.

National Institutes of Health, 1985, Report of the National Institutes of Health Ad Hoc Working Group to Develop Radioepidemiology Tables, NIH Publication No. 85-2748, U.S. Government Printing Office, Washington, DC.

Preston, D. L., and Pierce, E. A., 1987, The effects of changes in dosimetry on cancer mortality, risk estimates in the atom bomb survivors, RERF Tech. Rep. 9-87, Radiation Effects Research Foundation, Hiroshima.

Rodriquez, A., and Alpen, E. L., 1981, Cell survival in spheroids irradiated with heavy ion beams, Radiat. Res. 85:24.

Roesch, W. C., ed., 1987, Final report of Joint US-Japan Reassessment of Atomic Bomb Radiation Dosimetry in Hiroshima and Nagasaki, Vol. 1, Radiation Effects Research Foundation, Hiroshima.

Ron, E., Modan, B., and Boice, J. D., Jr., 1988, Mortality following radiotherapy for ringworm of the scalp, Am. J. Epidemiol., in press.

Rowland, R. E. and Lucas, H. F., Jr., 1984, Radium-dial workers. in: Radiation Carcinogenesis: Epidemiology and Biological Significance, J. D. Boice, Jr. and J. F. Fraumeni, Jr. (eds.), pp 231-240, Raven Press, New York.

Rust, D. M., 1982, Solar flares, proton showers and the Space Shuttle, Science 216:939.

Sinclair, W. K., 1986, Radiation protection standards in space, Adv. Space Res. 6(11):335.

Sinclair, W. K., 1987, Failla Memorial Lecture. Risk, research and radiation protection, Radiat. Res. 112:191.

Storer, J. B., Mitchell, T. J. and Fry, R. J. M., 1988, Extrapolation of the relative risk of radiogenic neoplasms across mouse strains and to man, Radiat. Res., in press.

Tatsuzaki, H., Inada, T., Shimizu, T., Arimoto, T., Satoh, S., and Akisada, M., 1987, Early skin reaction following 250 MeV proton peak irradiation, J. Radiat. Res. 28:150.

Todd, P. W., 1983, Unique biological aspects of radiation hazards - an overview, Adv. Space Res. 3(8):187.

Urano, M., Verhey, L. J., Goitein, M., Tepper, J. E., Suit, H. D., Mendiondo, O., Gradoudas, E. S., and Koehler, A., 1984, Relative biological effectiveness of modulated proton beams in various murine tissues, Int. J. Radiat. Oncol. Biol. Phys. 10:509.

Wood, D. H., Yochmowitz, M. G., Hardy, K. A., and Salmon, Y. L., 1986a, Animal studies of life shortening and cancer risk from space radiation, Adv. Space Res. 6(11):275.

Wood, D. M., Yochmowitz, M. G., Hardy, K. A., and Salmon, Y. L., 1986b, Occurrence of brain tumors in Rhesus monkeys exposed to 55 MeV protons, Adv. Space Res. 6(11):213.

Worgul, B. V., 1986, Cataract analysis and the assessment of radiation protection in space, Adv. Space Res. 6(11):285.

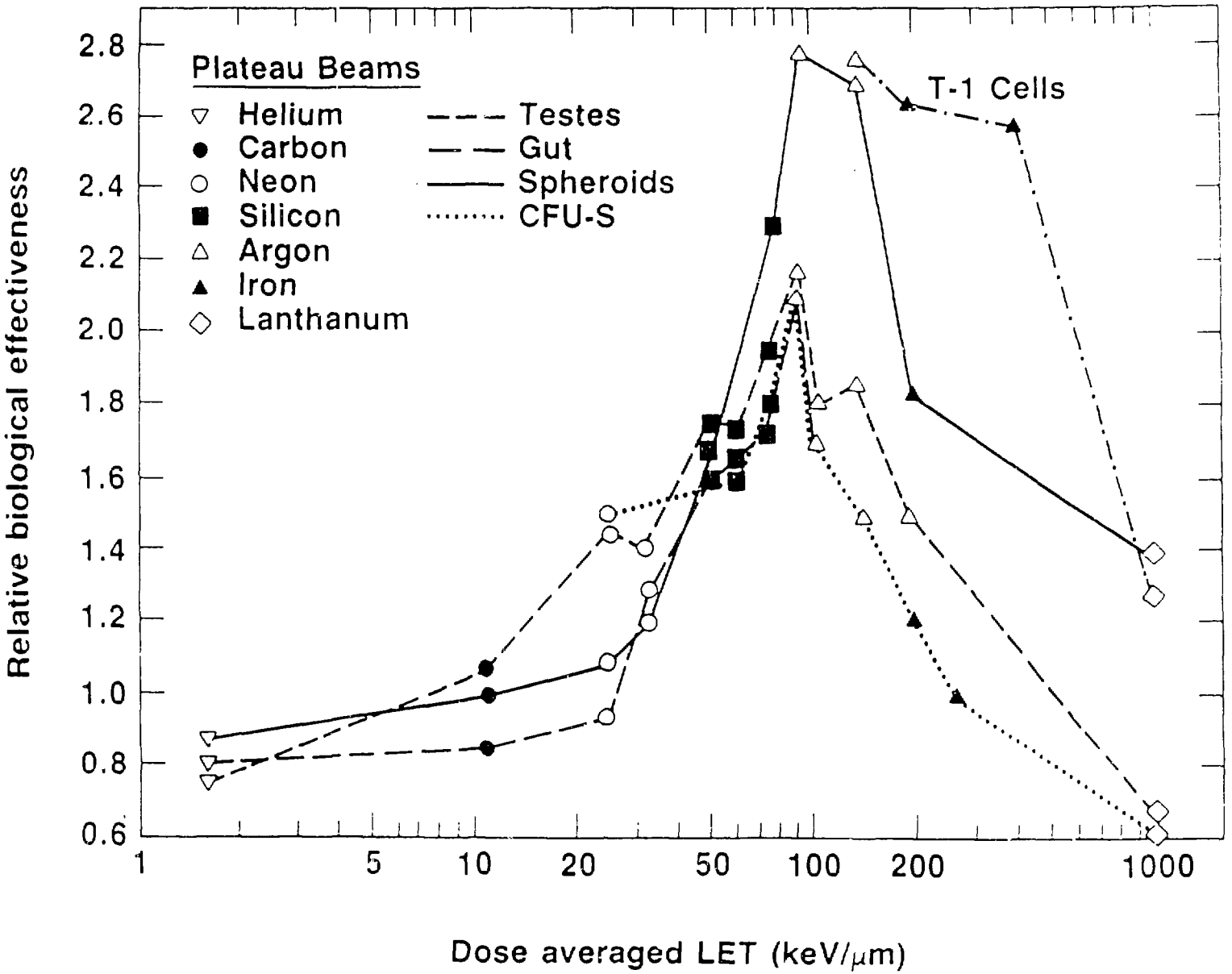
Yang, T. C., Craise, L. M., Mei, M.-T., and Tobias, C. A., 1985, Neoplastic cell transformation by heavy charged particles, Radiat. Res. 104S:177.

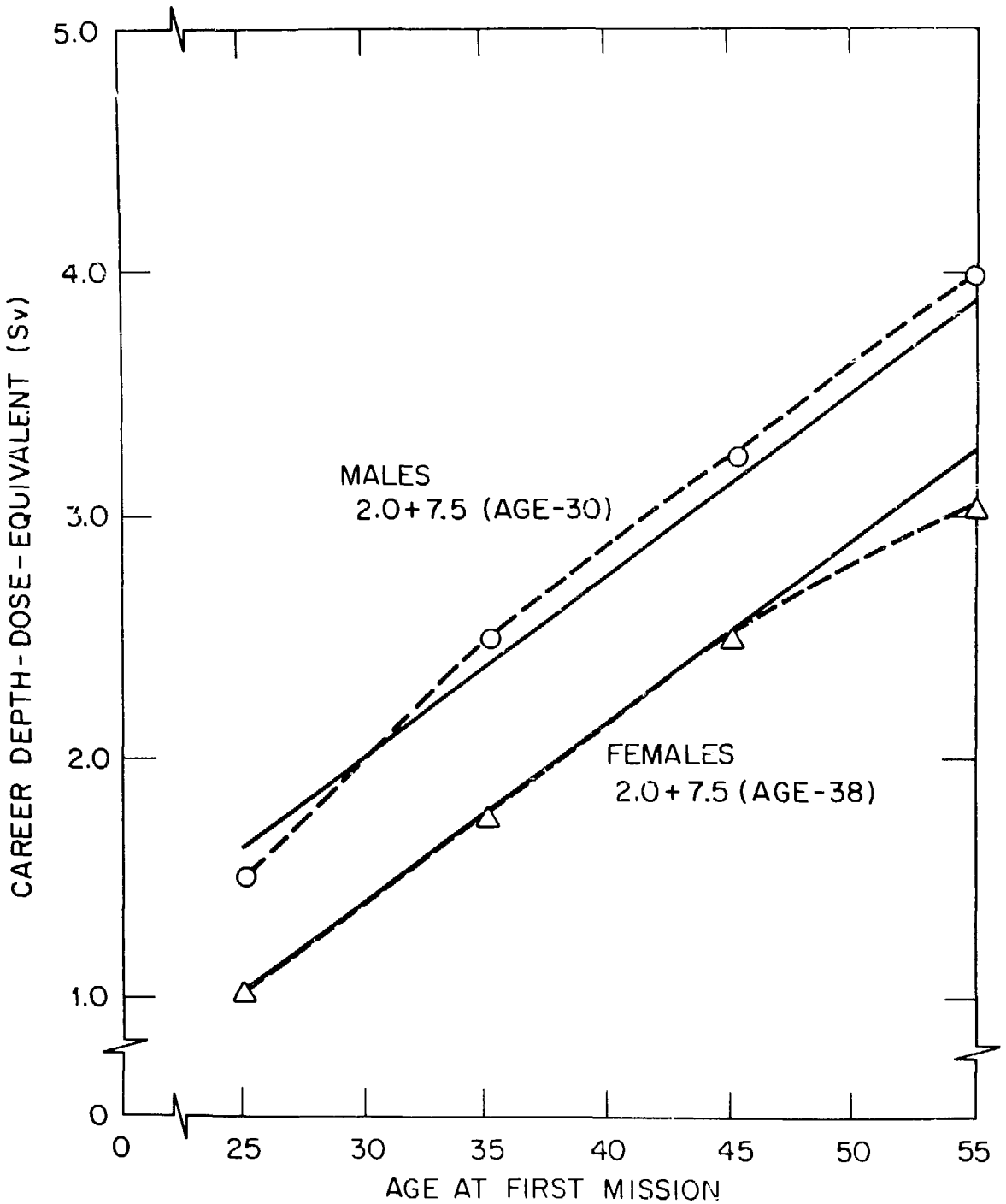
FIGURE LEGENDS

Figure 1. RBE for acute effects in normal tissues as a function of dose-averaged LET (keV/μm). Testes: Alpen and Powers-Risius, 1981; Gut: Alpen et al., 1980; Spheroids: Rodriquez and Alpen, 1981; CFUs: Ainsworth, 1986a; T-1 cells: Blakely, personal communication.

Figure 2. Recommended career depth-dose equivalents (Sv) as a function of age at first exposure. Females Δ--Δ and Males: o--o.

R.B.E for acute effects in normal tissues




5.0
4.0
3.0
2.0
1.0
0
0
25
30
35
40
45
50
55
CAREER DEPTH-DOSE-EQUIVALENT (Sv)
AGE AT FIRST MISSION
MALES
2.0+7.5 (AGE-30)
FEMALES
2.0+7.5 (AGE-38)