SPACE SCIENCE BOARD

Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems

Radiobiological Advisory Panel

Committee on Space Medicine

1970

National Academy of Sciences

RADIATION PROTECTION GUIDES AND CONSTRAINTS FOR SPACE-MISSION

AND VEHICLE-DESIGN STUDIES INVOLVING NUCLEAR SYSTEMS

Report of the Radiobiological Advisory Panel
of the Committee on Space Medicine

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National Academy of Sciences--National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1970

Available from
Space Science Board
2101 Constitution Avenue
Washington, D.C. 20418

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INTRODUCTION

At the request of the National Aeronautics and Space Administration, the Radiobiological Advisory Panel of the Space Science Board's Committee on Space Medicine, held a series of meetings (October 29-30, 1969, NASA-MSC, Houston; December 4-5, 1969, NAS, Washington, D.C.; and February 27-28, 1970, NASA-MSC) to formulate tentative radiation protection guides to be used as criteria in mission-planning and vehicle-design studies for manned space operations contemplated during the next 10 to 20 years. The bases for the Committee's deliberations are contained in the four Appendixes to this report: Appendix A, a letter from Charles A. Berry, M.D., Director of Medical Research and Operations, NASA-MSC, dated November 24, 1969, to Herbert G. Shepler, M.D., Secretary of the Radiobiological Advisory Panel, in which radiation design criteria are suggested; Appendix B, a letter from Mr. Milton Klein, Manager of the Space Nuclear Propulsion Office of the U.S. Atomic Energy Commission, to Dr. Shepler, dated November 20, 1969, which describes the reusable nuclear rocket program, the proposed missions for reusable systems, and suggested radiation design criteria; Appendix C, a letter from Mr. George P. Dix, Chief of the Safety Branch, Space Nuclear Systems Division of the U.S. Atomic Energy Commission, to Dr. Shepler dated November 25, 1969, including a publication on a 25-kWe reactor-thermoelectric power system for manned orbiting space stations; and Appendix D, NASA document MSC-00183 entitled "Radiation Environment for the 1975-1985 Space Station Program," which predicts radiation exposure rates as a function of uniform cylinder wall thickness (g/cm^2 of aluminum) for a 270-nautical-mile, 55° inclined orbit, a 200-nautical-mile polar orbit, and an equatorial earth-synchronous orbit. In addition, the NASA-MSC staff conducted extensive briefings of the Panel on contemplated manned operations of the next one to two decades, the representatives of the AEC's Space Nuclear Systems Division and Space Nuclear Propulsion Office conducted briefings on the types and characteristics of nuclear systems to be employed.

Manned space operations contemplated during the next decade or two will differ from those of the Apollo series in that (a) larger numbers of personnel will be involved; (b) mission times will be longer which will increase the probability of solar-flare interception and the total accumulated exposure from space-ambient background; and (c) nuclear systems will be utilized both for propulsion and on-board power requirements. Long-range missions will consist of nuclear-powered, deep-space expeditions such as the Mars landing and orbital space station and space base operations, eventually including on-board nuclear power and a nuclear stage orbit-to-orbit shuttle system. In all these operations, radiation exposure of crews may be broadly categorized as "unexpected" and "expected" (1). In the former category are exposures from solar-flare events, emergency repair of nuclear systems, and high-altitude nuclear test detonations if such should occur. Expected exposures will result from the earth's trapped radiation, galactic cosmic radiation, and radiations from nuclear systems. Exposures from expected sources are amenable to reasonably accurate prediction. Exposure from nuclear systems should be most predictable of all, and its control will be largely a matter of trade-off between acceptable levels of exposure and shielding weights. In this case, the radiations involved are not unusual and consist primarily of neutrons and gamma rays with which the nuclear-energy industry has had considerable experience. For the amounts of power required, radiation levels associated with fission reactors especially will be quite high, and adequate shielding to maintain crew exposures from nuclear radiation plus space radiation within limits established for terrestrial occupational exposure appears impractical. It seems necessary, therefore, to consider space missions of the next decade or so as being unusual occupations in which a higher than conventional radiation risk will have to be accepted.

GENERAL CONSIDERATIONS

It is necessary to establish at this time preliminary radiation-risk criteria and protection guides for the next 10 to 20 years of manned space operations to provide guidance for spacecraft-design and mission-planning studies already under way or contemplated for the near future. Unfortunately, establishment of risk criteria and protection guides for this purpose is a difficult undertaking fraught with a number of questions and problems, both philosophical and technical.

Philosophical Questions

The first philosophical question in the establishment of acceptable radiation-protection guides well may be, "Acceptable to whom?" For this reason, crew members, who will be volunteers, should be as thoroughly informed as possible as to the nature and level of the radiation risk. Any prescribed radiation limits should conform to the guidelines issued by the Federal Radiation Council on the basis of the risk-versus-gain philosophy. The guides should be in line also with the consensus of the informed radiobiological and medical community. Equally important, the guides should be acceptable in terms of technical and fiscal feasibility to the design and flight engineers and those responsible for federal appropriations. Still another troublesome philosophical point in establishing guides involves the responsibility for risk-versus-gain judgments. Spacecraft-design and mission-planning studies require specific numbers. To give such numbers requires, in essence, a judgment as to the operation's gain or worth to the nation's space goals in terms of human risk.

To avoid having to make such judgments, the Radiobiological Advisory Panel of the Space Science Board's Committee on Space Medicine, in its 1967 study (2) gave its best judgment on the probabilities of radiation effects in man as a function of exposure. It was the Panel's opinion and philosophy that (a) radiation-protection aspects of each type of manned space operation should be considered individually in context with a risk-versus-gain philosophy and the magnitude of other risks inherent in the operation, (b) the Panel's primary responsibility was to evaluate the potential radiation risk in probabilistic terms if possible, and (c) the Panel had neither the responsibility nor competency to evaluate gain.

It would seem reasonable to continue the above philosophy in establishing radiation-protection guides for the next decade or two of manned space exploration. The remaining philosophical question, of course, is, "To whom should the responsibilities of evaluating risk and gain be relegated?" The Panel has been given the responsibility of advising the Space Science Board, through its Committee on Space Medicine, about protection criteria and the nature and level of radiation risk. This is assumed by the Panel to be the limit of its activities. Evaluation of gain that will ensue from accepting a specific level of risk (of which radiation is only a part) depends on a wide range of general and specific scientific and subjective judgments and should be the responsibility of those most informed about the aims and goals of the nation's space program.

Technical Problems

The primary technical difficulties relative to establishing acceptable protection guides are (and will continue to be) in connection with the quality and extent of available data on man's response to radiation exposure. If guides less restrictive than those for conventional occupational exposure are to be established, quantitatively reliable information on the levels of human responses as a function of dose and conditions of exposure must be derived. This can be done, of course, only on the basis of existing knowledge. Current knowledge of man's radiation responses comes from medical uses of radiation involving ill subjects, radiation accidents, the atomic bombings of Hiroshima and Nagasaki, and occupational exposure prior to full appreciation of the potential hazards of ionizing radiation. The conditions for all these sources of information were those inherent in particular situations and were not those that could best provide the desired general information. However, there is a considerable body of such data that, when supplemented by the vast amount of laboratory animal experimentation, supports establishment of dose-response trends in man. The greatest weakness lies in the fact that the quantity and nature of the data are such that they do not provide an adequate basis for statistical derivation of confidence limits when applied to space conditions. In other technical problem areas, neither human observations nor sufficient laboratory animal data exist upon which to base a satisfactory evaluation of risk. Comparison of the high-Z and high-energy (HZE) particle component of galactic cosmic radiations on Apollo earth-orbital flights and Apollo lunar missions 11 and 12 shows the numbers of such particles to be a factor of about 6 greater in the latter missions (3). There is little information available on either man or animals regarding the inactivation cross section by high-Z particles of nondividing cells that compose the primary functional portion of the central nervous system. Neither is there information on the degree of redundancy in the brain and the possible consequences of progressive destruction of nondividing nerve cells during long-duration, deep-space missions. The question of biological effects of HZE particles has been accentuated by the report of visual light flashes, even with eyes closed, by Apollo 11, 12, and 13 crews.

Another difficult technical question is that of interaction of radiation exposure with exposure to other factors such as weightlessness inherent in the space environment.

Radiation Effects Relevant to Spaceflight

Radiation effects in a complex organism such as man range from subtle changes at the molecular and cellular levels to death in a matter of minutes, depending, of course, on exposure conditions. Not all these effects are of immediate practical importance in manned spaceflight operations. The Panel considered the matter of genetic risk and concluded that the problem was not of immediate concern. Flight programs over the next decade will remain developmental in many respects, and comparatively small numbers of persons will be involved, most of whom will be over 30 years of age. Any possible mutational contribution from this group will be diluted in the population gene pool by a factor estimated to lie between 1×10^5 and 5×10^6. The problem is really more a concern for the individual crew member and should be managed through appropriate counseling on specific genetic endpoints and on voluntary methods by which avoidance or partial control may be accomplished. The Panel considers that the immediate problem is to maintain operational capability and that somatic effects are more relevant than genetic effects. Relevant somatic effects may be classified as early and late on the basis of an arbitrarily chosen time of appearance as follows (4):

1. Early Effects (appearance within hours to 60 days)
    a. Skin erythema and desquamation
    b. Prodromal response (nausea, vomiting, etc.)
    c. Hematological depression
    d. Lethality
2. Late Effects (appearance within a few to many years)
    a. Permanent or delayed skin changes
    b. Increased incidence of cataract
    c. Increased incidence of leukemia and other neoplastic disease
    d. Infertility and sterility
    e. General nonspecific life shortening

Early effects are highly relevant to short- and long-range missions alike in that they may produce sufficient impairment to result in abortion or loss of the mission. It is imperative, therefore, that spacecraft design and mission planning be such that the probability of exposures sufficient to elicit early responses be quite low regardless of the length of the mission. The probability of interception of a major solar flare increases with increasing mission duration, which suggests the advisability of providing a specially shielded area for protection from solar events on long-duration missions outside the earth's magnetosphere. However, early effects are dose-rate-dependent threshold phenomena, which should make the emergency shielding problem less difficult. Dose-response relationships for early effects in man and what is known of their dependence on dose rate and other factors are summarized in Reference 2.

Late effects have little relevance to specific or individual short-duration missions. They would appear to have considerable relevance, however, to accumulated career exposures and long missions of the character contemplated during the next decade or two. It is not inconceivable that active careers could approach 10 or more years, and single missions could approach 5 years. The requirement for long exposure times and relatively larger numbers of participants suggests establishment of career and mission exposure guides on the basis of risk of late effects, particularly in view of the fact that accumulation of high doses at high dose rates will have to be avoided to eliminate mission failure from early responses. The use of nuclear systems will contribute a predictable fraction of the accumulated low-dose-rate exposure, the extent of which will be controlled by shielding feasibility.

CONSIDERATION OF APPENDIXES A-D

After a review of the material in Appendixes A-D, the Panel was of the opinion that the various radiation-protection guides and constraints suggested for design study purposes were not inordinately lax and, in some cases, were somewhat restrictive in comparison with other risks inherent in the types of operations contemplated during the next decade or so. From this material, it appears that convenience in design studies has resulted in consideration of radiation-protection criteria for nuclear systems radiation and natural space radiation separately. As an example, Appendix A recommends for the space station/base a crew exposure of 55 rem in a stay time of 1 year (0.15 rem/day x 365 = 55 rem/year) from nuclear systems and 25 rem/year from all natural environmental radiation. This appears a bit restrictive on natural environmental protection criteria, because Appendix D predicts the yearly environmental exposure rate for a 270-nautical-mile, 55° inclined orbit and an earth-synchronous, 0° inclined orbit to be approximately 20 and 40 rem, respectively, at 4 g/cm^2 shielding, beyond which exposure rates change slowly with increasing shield thickness. It would appear more consistent and flexible to establish a maximum acceptable career or mission exposure limitation for nuclear plus natural radiation with restriction on accumulation rate but with freedom of trade-off between the two. In making such trade-offs, however, adequate allowance must be made to cover the contingency of unexpected exposure, the level of which is largely unpredictable.

THE CONCEPT OF A "REFERENCE" RISK

The recommendation of specific numbers as radiation-protection guides and constraints for vehicle-design and space-mission planning studies requires either explicit or implied risk-versus-gain judgments and deprives those responsible for the nation's space program of flexibility. Since such judgments depend on many things not obvious to the radiobiology and medical communities, it seems reasonable to recommend a primary reference risk that may be used as a point of normalization for plans and operations involving different numbers of personnel, different risk-versus-gain evaluations, and different degrees of operational complexity. Under Federal Radiation Council philosophy, government agencies concerned have the freedom to adopt lower or higher levels of risk for specific situations with adequate justification. Two different situations may be space station/base and planetary mission operations. Under demanding circumstances near mission finalization, the latter may justify risk greater than the reference risk, while under ordinary circumstances the former may justify risk less than the reference risk.

As operations of the next 10 to 20 years will involve protracted accumulation of radiation exposure from nuclear power systems and the natural space reduction environment, it seems reasonable to derive the reference risk on the basis of delayed or late radiation effects. Of the five late somatic effects listed previously, only two can be considered as major determinants: increased probability of leukemia and other neoplastic disease, and general nonspecific life shortening. Life shortening may be set aside as the primary determinant for several reasons. Probability statements regarding life shortening are generally applicable to populations rather than to individuals, and the effect is not time-limited (that is, the manifestation is distributed over the whole after-expectation of life following irradiation). It is the summation of many subtle changes in individuals within the population group. Although extensive, high-quality animal data exist that support some reasonable extrapolation to man, direct human experience is still limited and of poor predictive value.

On the other hand, leukemia and other neoplastic diseases represent a specific set of endpoints that permit probability statements at the individual level and that, for leukemia at least, can be time-limited. The available human data are rather detailed, are derived from several independent experience groups, and show surprisingly good consistency.

In addition, animal data are extensive and consistent with the human experience. The Panel, therefore, has chosen to derive the reference risk on the basis of the probability of leukemia and other radiation-induced neoplasms. The reference risk will be related to the accumulated dose equivalent that will result in a probability of radiation-induced neoplasia equal to the natural probability for the specific population over the period of risk for which human data are available--about 20 years. If it is assumed that space careers begin at age 30 to 35 and that a significant risk of death from radiation-induced neoplasms persists for at least 20 years after exposure, then a risk period extending from age 35 to age 55 would define the logical age group to use as a basis for derivation of the natural or spontaneous neoplastic disease risk.

Specifically, the Panel proposes that the primary reference risk should correspond to an added probability of radiation-induced neoplasia over a period of about 20 years that is equal to the natural probability for the specific population under consideration. The Panel is of the opinion that this added risk is probably low in comparison with the total risk from all sources associated with missions; however, the Panel expressly wishes to avoid making the judgment that this degree of added risk is allowable for a given mission or that this added risk is offset by expected gain.

Primary Data and Assumptions

Table 1 shows the natural incidence of death from neoplasms of various sites for the U.S. white male population between the ages of 35 and 55 years. These data were taken from the WHO Statistics Annual 1964 (5) and are complete through 1961. The data indicate that the probability of a U.S. male dying from leukemia between the ages of 35 and 55 is 1.04×10^{-3} or 0.1 percent, and from neoplastic disease of all sites it is 22.9×10^{-3} or 2.3 percent.

Current estimates of risk from radiation-induced leukemia come largely from observations of the Japanese atmoic bomb survivors, the British ankylosing spondylitic patients treated with radiation, and practicing U.S. radiologists between 1920 and 1950. Application of the leukemia data from the Japanese survivors to assessment of space radiation risk is complicated by a number of factors: (a) the complexities and uncertainties in dose estimation; (b) exposures were to a mixture of neutrons and gamma rays, with the neutron contribution much greater at Hiroshima than at Nagasaki; (c) the dose was delivered in a single prompt exposure; (d) the mean age of the exposed Japanese groups (which included women and children) was relatively lower than that of the space crews under consideration; and (e) the rate of increase with age in natural incidence of leukemia in the Japanese and U.S. populations diverges rapidly beyond approximately age 40 and is much greater in the U.S. population. Technically, the conditions in (b) call for quality-factor (QF) and depth-dose considerations when converting risk per unit dose (rad) to risk per unit dose-equivalent (rem).

TABLE 1 Cancer Deaths in U.S. Males (1961) in Age Group 35 to 55 Years (5)

Sites	Deaths per 100,000 35-39	40-44	45-49	50-54	Yearly Average 35-55	20-Year Total	20-Year Probability (percent)
Buccal cavity and pharynx	0.7	2.4	5.4	10.7	4.8	96.0	0.096
Esophagus	0.5	1.8	3.7	7.4	3.3	67.0	0.067
Stomach	1.8	3.5	7.5	14.7	6.9	137.5	0.137
Intestines	2.8	4.9	8.6	17.4	8.4	168.5	0.169
Rectum	0.8	1.9	3.8	7.1	3.3	68.0	0.068
Larynx	0.2	0.7	2.0	4.1	1.7	35.0	0.035
Trachea, bronchi, and lung	7.4	18.1	38.3	76.1	34.9	699.5	0.699
Prostate	0.1	0.3	1.3	4.2	1.5	29.5	0.030
Skin	2.0	2.6	3.3	4.6	3.1	62.5	0.062
Bone and connective tissue	0.7	1.0	2.0	2.5	1.5	31.0	0.031
All other unspecified	10.5	19.2	32.3	59.0	30.2	605.0	0.605
Leukemia and aleukemia	3.0	3.9	5.3	8.6	5.2	104.1	0.104
Lymphosarcoma, etc.[a]	5.7	7.7	9.8	13.9	9.3	185.5	0.186
TOTAL ALL SITES	36.2	68.0	123.3	230.3	114.1	2289.1	2.289

[a] Includes other neoplasms of lymphatic and hermatopoietic system, including Hodgkins disease.

The most complete analysis of the Japanese data to date is contained in a manuscript by Ishimaru _et al_. (6), which uses all the clinical data through September 1966 and the currently accepted 1965 dose estimates (7) for both neutron and gamma-ray components. Assignment of a QF of 5 to the neutron component of dose gave the best fit to the data and indicated a leukemia risk of 1.5×10^{-6}/rem/year at Hiroshima and 1.8×10^{-6}/rem/year at Nagasaki. The former result is based on 88 cases, the latter on 29. Averaging all data, after calculating the rate of risk per rem for each point weighted by $\sqrt{N}$, gives a leukemia-induction risk of 1.54×10^{-6}/rem/year. The error in this estimate is uncertain, but it is probably good to a factor of 2 or better. As the Japanese survivors all received a single prompt exposure, nothing can be said about the possibility of a dose-rate effect. If indeed a dose-rate effect exists, use of the average value derived from the Japanese bombings would be conservative.

The British spondylitic patients received total cumulative x-ray exposures ranging from 112 to more than 2000 R from one course of fractionated exposures (over about 30 days) to 8 courses of therapy with separations by as many as 8 years. Exposures were confined to limited areas of the body that often involved the spine and pelvis. When converted to equivalent exposure of the total bone marrow, a linear dose-response relationship suggests a radiation-induced leukemia risk of $\sim 0.7 \times 10^{-6}$/rem/year $\pm \sim 50$ percent over the range of 300 to 2000 rem (8,9). It is relevant to note that these were diseased patients given partial-body exposure in a wide variety of distributions, and that exposure was widely fractionated, although exposure rates for individual fractions were several roentgens per minute.

Increased incidence of leukemia in early U.S. radiologists is well established. Lethality records for the 14-year period 1948-1961 showed an excess of leukemia deaths in radiologists of $168/10^{6}$/year (8). Based on the linear dose-response relationship for the Japanese survivors, the excess leukemia incidence in radiologists would correspond to a prompt exposure of ~100 rem. Little is known about the magnitude and distribution of the dose received by the early radiologists, but it is generally accepted that doses probably of several hundred rads at least were received chronically over periods of up to 40 years. One estimate (10) is that the average 40-year-career exposure might have been as much as 2000 R. When compared with the Japanese survivors, the low leukemia incidence observed in early radiologists suggests a real possibility of a dose-rate effect.

None of the above sources of information provides an adequate basis for unequivocal estimation of risk from other radiation-induced neoplasms. However, the Japanese data do show an increased incidence over the control population of neoplasms other than leukemia with exposures above 100 rem. A comparison was made between the number of cases of leukemia and other forms of cancer during the period 5 to 15 years after exposure. The ratio of nonleukemic neoplasms to leukemia was 0.8 with a standard error of 0.4. Because of an apparently longer induction period for nonleukemic neoplasms than for leukemia, this ratio might be expected to increase with time (8).

Delayed radiation effects in atomic bomb survivors have been reviewed recently by Miller (11). In his summary, he states that increase in neoplasms other than leukemia in the exposed Japanese survivors has been observed. Data are adequate to establish a dose-response relationship that indicates that thyroid cancer appears certain to have been induced. Twice the normal frequency of lung cancer has been reported among persons exposed to doses of 90 rads or greater; however, the data do not support a dose-response relationship and, therefore, do not unequivocally establish cause and effect. The same has been reported also for breast cancer in women. The data at present do not support establishment of dose-response relationships in the Japanese survivors for neoplasms of specific sites other than leukemia and, perhaps, tumors of the thyroid.

There appears to be an increased incidence of neoplasms other than leukemia in the British spondylitic patients (12). During a 13-year period following the first exposure, it was estimated that excess deaths from leukemia and from other cancers arising in heavily irradiated tissues, which could be attributed to radiation, were 4 per 1000 patients and 6 per 1000 patients, respectively (13). The data on deaths in U.S. radiologists from neoplasms other than leukemia are equivocal but suggest a slightly increased incidence (14).

For lack of more definitive observations, Committee I of the International Commission on Radiological Protection (15) concluded that a reasonable estimate of risk from nonleukemic neoplasms over a 20-year period following exposure was that it was about equal to the risk from leukemia. On this basis, and taking the radiation-induced leukemia risk for the Japanese survivors as 1.5×10^{-6}/rem/year, the 20-year risk from leukemia plus other radiation-induced neoplastic disease would be 6×10^{-5}/rem. This estimate may be conservative in that (a) it assumes a linear dose-response relationship below 100 rem, and (b) it assumes no dose-rate dependence of oncogenic response as it is based on response of the Japanese survivors who received a single prompt exposure. Although dose-rate dependence of radiation-induced leukemia and other neoplastic disease in man has not been established unequivocally, animal studies indicate that dose-rate dependence is quite likely, and that, at exposure rates of 1 rem/day or less, the induction ratio in mice may be lower by as least a factor of 5 than at much higher rates (16, 17). Observations of the spondylitic cases and U.S. radiologists suggest also that a dose-rate dependence of leukemia induction in man may exist. The conservatism introduced by not taking dose-rate dependence into account will compensate to some degree for the effect of a possible underestimation of the induction ratio of leukemia to other types of neoplasms.

Derivation of Dose Equivalent Corresponding to Reference Risk

Table 1 shows that the probability of a U.S. male developing leukemia during the 20-year period from age 35 to age 55 is 0.104 percent and that his total probability of developing cancer during the 20-year period is 2.3 percent. Assuming that the risk from radiation induction of leukemia is 1.5 x 10^{-6}/rem/year and that the risk from all other neoplasms is the same (total risk = 6 x 10^{-5}/rem/20 years), the whole-body exposure required to double the natural risk of neoplastic disease during the age interval from 35 to 55 years would be 2300 x 10^{-5} ÷ 6 x 10^{-5} = 383 rem. It is proposed, therefore, that the exposure associated with the primary reference risk (i.e., an additional risk equivalent to the natural risk of death from malignant disease in the U.S. white male population over the 20-year period age 35 to 55) be taken as a dose-equivalent of 400 rem at the average depth of the bone marrow (5 cm).

ANCILLARY EXPOSURE AND EXPOSURE RATE CONSTRAINTS

Exposure rate constraints are not introduced in connection with the primary reference risk (i.e., increased probability of malignant disease). As defined above, the reference risk exposure is derived on the basis of observations of oncogenic response to a single prompt exposure with no adjustment for a possible exposure-rate dependence. In this respect, the primary reference risk may be considered maximal. However, it is considered necessary to introduce exposure and exposure rate constraints as an adjunct to the primary reference risk to eliminate or minimize the probabilities of responses other than those germane to the reference-risk concept and the biological effects associated with it. The principal responses not germane to the primary reference risk are rate-dependent threshold phenomena that increase in incidence and severity with increasing dose once the threshold is reached and may include both early and late responses. An exposure of 400 rem at a depth of 5 cm accumulated in a few days will have a high probability of producing early death. An exposure of 50 rem in 2 to 4 hours or less may result in a 10 percent probability of nausea. Too rapid accumulation of exposure at 5-cm depth can produce significant undesirable effects (e.g., bone marrow aplasia) quite aside from increased probability of malignancy.

Exposure Accumulation at Mean Depth of Bone Marrow (5 cm)

At continuous exposure rates of about 1 rem/day or less, the rate of radiation injury and recovery of the hematopoietic system will approach an equilibrium and a steady state may be maintained for long periods of time. This suggests that the rate of accumulation of exposure at a depth of 5 cm should be held to 1 rem/day or less. To allow for occasional periods of unexpected exposure at rates in excess of 1 rem/day, the daily average over a period of 1 year should be considerably less (say, 0.2 to 0.4 rem/day). At 0.2 rem/day, the yearly total accumulation would be about 75 rem. Normalized to the primary reference risk exposure (400 rem), this restriction limits careers and missions at the continuous maximum yearly rate to 5 to 6 years. The yearly accumulation should be subjected to the added rate restriction that the average accumulation for any quarter year should not exceed 35 rem, with allowance for exposure for two consecutive quarters at this rate provided the tour of duty is followed by a 6-month period without additional exposure. The quarterly exposure should be restricted further so that accumulation in any consecutive 30-day period does not exceed 25 rem. If delivered in a single prompt exposure, 25 rem would have no demonstrable effect (except on sperm count, cytology of some lymphocytes, and perhaps chromosomal abnormalities). There are no compelling reasons to feel that equilibration of bone-marrow injury and repair would not be maintained for long periods and that bone-marrow aplasia would occur at twice the total exposure (800 rem) accumulated at twice the specified rates.

It is generally recognized that any nonspecific life-shortening effect can be related to the average marrow exposure (2). This will hold regardless of such variations in the exposure pattern as partial-body, whole-body, high-dose-rate, or low-dose-rate exposure or other factors causing nonuniformity of exposure. If the average exposure rate over a long period of time is below 1 rem/day, the life-shortening effect will be minimal and probably in the range of 0.5 to 3.0 days/rem. Exposure at the reference risk level, therefore, may impose an actuarial risk of loss of 0.5 to 3.0 years from the normal 40- to 45-year after-expectation of life for the age group under consideration.

Exposure Accumulation at Mean Depth of Basal Layer of Skin (0.1 mm)

Responses of the skin to radiation exposure are highly rate-dependent. Patients given fractionated exposures (85 R/week) of soft x rays (60 to 100 kV) show no late radiation sequelae with accumulated exposures of 1000 R and less. With exposures between 1000 and 2600 R, late sequelae of cosmetic interest only (pigmentary changes, telangiectasia) may occur in about 1.5 percent of cases (18). These and other observations suggest that an exposure of 1200 rem at the average depth of 0.1 mm protracted over 100 days or longer would not produce any significant delayed skin changes even when relatively large areas are exposed. Although further protraction of exposure undoubtedly would lessen the probability of response even more, the observations do not justify extrapolation to accumulation times anticipated in space operations of the next decade. Compared to the primary reference risk level of 400 rem at 5 cm, 1200 rem to the skin would appear quite conservative and indicate an exposure ratio of ~3 between exposure at 0.1-mm and 5-cm depths. Application of this ratio as a purely arbitrary means of deriving skin exposure-rate constraints, ancillary to the reference risk exposure, gives a yearly accumulation limit of 225 rem, a quarterly limit of 105 rem, and a 30-day limitation of 75 rem.

Both the probability and severity of skin responses increase nonlinearly with increasing exposure. A protracted exposure to relatively large areas of 2400 rem at an average depth of 0.1 mm might be expected to increase the incidence of mild late sequelae, including slight atrophic changes to no more than 5 to 10 percent. These late changes should not be severe nor result in any areas of necrosis in more than an occasional, unusually sensitive individual. Exposures that produce a small probability of skin necrosis and fibrosis must be avoided. From 5 to 25 percent of cases of radiation necrosis reportedly progress to squamous- or basal-cell carcinoma. However, skin exposure will not be limiting except under very unusual circumstances involving light shielding from low-energy electrons and protons.

Exposure Accumulation at Depth of Ocular Lens (3 mm)

The dose-response curve for radiation induction of cataract seems to be highly sigmoid, particularly for low-LET radiation, and there appears to be a threshold below which even minor opacities do not occur even at long times after exposure (12). Above the threshold, however, the incidence of lens changes increases nonlinearly with increasing exposure, the time to appearance is shortened, and the number that are progressive to the stage of true cataract with visual impairment increases. Protraction of exposure increases somewhat the dose required to produce a given level of response (2, 19). Available data suggest that 600 to 700 rem delivered over a period of 1 to 5 years should be near the threshold for production of lens opacities, while 1200 rem might result in ~10 percent probability of the development of definite cataract resulting in impaired vision. It seems reasonable, therefore, as an adjunct to the reference risk exposure to suggest a commensurate dose-equivalent of 600 rem to the lens, which gives a ratio of 1.5 between exposures at 3-mm and 5-cm depth. Accepting this ratio, the yearly accumulated exposure at the depth of the lens would be approximately 110 rem, the quarterly accumulation 50 rem, and 30-day accumulation about 35 rem.

Exposure Accumulation to the Germinal Epithelium (3 cm)

The germinal epithelium is probably the most sensitive tissue in the human body. A prompt dose of only 15 rem will drop the sperm count of a normal healthy man by 50 percent or more in about 60 days, and a prompt dose of 100 rem will produce complete absence of sperm in 100 days or so. Because there are no human data on effects of protracted or divided exposure on spermatogenesis, one must rely on animal experiments. Here the evidence indicates that divided or protracted exposures may be more effective than prompt exposure because of the cyclic process of spermatogenesis (2). In the dog, the accumulation of 250 rem over a period of 8 years at a dose rate of 0.6 rem/week (approximately 0.1 rem/day) produced no significant change in sperm count. However, 156 rem accumulated during 1 year at the rate of 3 rem/week (0.43 rem/day) produced sterility in 80 percent of the animals and reduced sperm count in the other 20 percent. An exposure of 624 rem accumulated during 2 years at a rate of 6 rem/week (approximately 0.9 rem/day) resulted in pronounced atrophy of the epithelium and 100 percent sterility. It appears that accumulation of 75 rem at an average daily exposure rate of 0.2 rem may result in reduced sperm count that may be low enough to produce temporary infertility in a small percentage of cases. If exposure is continued at this rate for 2 to 5 years, temporary infertility will probably occur more frequently. Infertility will surely result with exposures of longer than 1 year at an average rate of 0.4 rem/day. From the strict radiological health view, oligospermia and sterility are of little consequence. The principal problem is one of psychological impact on the individual. Libido and potency are unaffected with prompt local exposures in excess of 600 rem. With local exposures approaching 600 rem, sterility may last for 3 or more years, but recovery ensues without serious physiological alterations.

It hardly seems within the competency of the Panel to propose an ancillary reference risk for exposure of the testicular epithelium, because the primary problem is not one of damage to physical health but, rather, one of psychological impact on the individual. If the possibility of oligospermia and temporary infertility is to be avoided, methods will have to be devised to keep the average daily exposure rate at a depth of 3 cm in the region of the testes in the range of or below about 0.1 rem/day. If avoidance of any psychological effects of possible oligospermia and temporary infertility is deemed important, it may be necessary to limit at one reference risk level the ratio of exposure at the mean depth of the testes (3 cm) to the exposure at 5 cm to ~0.5. This situation immediately introduces a contradiction in limits, as it is not physically possible to allow a greater dose at greater depth than the one of concern unless locally applied supplementary shielding methods are employed.

APPLICATION TO MISSION-PLANNING AND VEHICLE-DESIGN STUDIES

A number of factors enter into the choice of radiation-protection criteria for vehicle-design and operational planning, among which are (a) risk-versus-expected gain evaluation, (b) numbers of personnel involved, (c) trade-offs between radiation risk and other risks, (d) complexity of the over-all mission, (e) engineering and fiscal feasibility, and (f) turn-around or evacuation capability.

TABLE 2 Suggested Exposure Limits and Exposure Accumulation Rate Constraints for Unit Reference Risk Conditions

Constraint	Primary Reference Risk (rem at 5 cm)	Ancillary Reference Risks: 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 maximum		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 two consecutive quarters followed by 6 months of restriction from further exposure to maintain yearly limit.

Primary Reference Risk

The Panel has proposed a primary reference risk that corresponds to an added probability of radiation-induced neoplasia over a period of about 20 years that is equal to the natural probability for the specific population at risk. The Panel has further proposed that the primary reference risk exposure be taken as a dose-equivalent of 400 rem at the mean depth of the bone marrow (5 cm) irrespective of exposure rate. In this respect, the risk associated with the reference exposure may be considered maximal. The Panel has avoided making the judgment that the degree of added risk associated with the reference risk exposure is "allowable" for a given operation or that this added risk is offset by expected gain or other factors. The intent of this approach is to allow a reasonable degree of freedom in establishing radiation-protection criteria for operational-planning and vehicle-design studies that take the above factors into consideration and to provide a meaningful reference point for relative evaluation of protection criteria adopted for different situations. As an example, acceptance of a higher risk for planetary missions (involving, perhaps, a dozen or so personnel and greater need for trade-offs between radiation and other risks) than for space station/base operations (involving, perhaps, 50 to 100 personnel and evacuation feasibility) would seem both realistic and practical. It seems reasonable to the Panel also that over-all evaluation may indicate that some operations justify taking less than the primary reference risk while others justify taking considerably more.

Ancillary Reference Risks

Exposure-rate constraints are not necessary for the primary reference risk (increased probability of malignant disease) because the reference risk exposure (400 rem at the average depth of the bone marrow) was derived largely on the basis of response to a single prompt exposure. It seems necessary, however, to introduce ancillary reference exposure and exposure-rate constraints as an adjunct to the primary reference risk exposure to minimize the probability that some secondary risks might become limiting. Early responses, as well as late responses such as bone-marrow aplasia, cataract of the optic lens, delayed skin sequelae, and sterility, are dose-rate-dependent threshold phenomena that increase nonlinearly in incidence and severity with increasing exposure above the threshold dose. Any significant probability of exposures at exposure rates that would elicit early responses, of course, must be avoided, as they could result in loss of the mission. Table 2 summarizes exposure and exposure-rate constraints for the more significant delayed or long-term ancillary risks to be used as adjuncts to the primary reference risk. At the specified accumulation rates, the total accumulated exposures would not be expected to exceed the respective thresholds for early responses, bone-marrow aplasia, unacceptable late skin sequelae, lens opacities, and protracted sterility, and would be of no significance compared to the increased probability of death from malignant disease at one primary reference risk level. A doubling of the specified total exposure levels at twice the specified exposure rates would be expected to result in increased probability or severity or both of some of the ancillary risks, but the significance of such increases would appear still to be secondary to that of the increased probability of malignancy resulting from doubling of the primary reference risk exposure (800 rem at 5-cm depth). If, in the next decade or two of space operations, a situation should arise that justified more than twice the primary reference risk, the ratio of exposures at the respective depths of the secondary responses to that at 5 cm will have to be readjusted, as will the exposure-rate constraints, because of nonlinearity of the dose-response relationships of early and late secondary responses. As an example, 600 rem to the ocular lens delivered over 1 to 5 years will approach the threshold for opacity production, 1200 rem may result in a 10 percent probability of visually impairing cataracts, and 1800 rem will result in 50 to 75 percent probability of cataracts, the majority of which will progress to visually impairing lesions.

In essence, the radiation-protection criteria recommended in Table 2 are career exposure limits at one primary reference risk level and, therefore, automatically limit careers to 5 to 6 years if the exposure-rate limits are regularly reached. If careers are to exceed 5 to 6 years, exposure accumulation rates must be adjusted accordingly. For space station/base and orbit-to-orbit nuclear stage operations where turn-around or evacuation is feasible, the quarterly rates may be allowed for two consecutive quarters if followed by 6 months without additional exposure in order to keep exposure within the yearly accumulation rate restriction. For planetary operations (in which evacuation or turn-around feasibility is limited), if a particular mission results in exposure amounting to 50 percent or more of the accepted risk for such a mission, the crew's career should not include additional missions. As given, the protection criteria do not include allowances for uncertainties in design and planning, and the actual criteria used for planning and design studies should make allowances for such uncertainties.

Quality Factor (QF)

The exposure guides and accumulation-rate constraints recommended in the previous sections are dose-equivalents (DE) in rem at the mean depth of interest, where DE = rad x QF. QF is a factor introduced to make allowance for difference in biological effectiveness of radiations of different quality (LET). As currently used in radiation protection, QF is intended as a general value that assures that the risk from a specified maximum permissible dose of high-LET radiation never exceeds that from a maximum permissible dose of low-LET reference radiation. Current practice for evaluating QF from LET is to use a smooth curve drawn through the QF-LET values (Table 3) recommended by the International Commission on Radiological Protection (20).

TABLE 3 Relationship between QF and LET Recommended for Radiation-Protection Calculations (20)

LET_{∞} [a] (keV/μm in Water)	QF
3.5 or less	1
7	2
23	5
53	10
175	20

[a] LET_{∞} is the same as stopping power.

Beyond an LET of 175 keV/μm, corresponding to a QF of 20, the QF is assumed to remain constant. LET is taken as the local mean LET at the point of interest. The relative biological effectiveness (RBE) of densely ionizing radiation for production of lethality of cultured dividing cells reaches a maximum of about 6 to 8 in the LET range of 100 to 200 keV/μm and decreases essentially to unity at 1000 keV/μm (21, 22). The current method of evaluating QF may drastically overestimate the dose-equivalent for the HZE component of the galactic flux for production of neoplastic, skin, testicular, and, perhaps, ocular lens responses. Because of the unusual pattern of energy deposition in tissue by HZE particles, the concept of average LET, and therefore of average QF, breaks down. There is no logical basis on which to derive a meaningful average QF for effects of long-term HZE particle exposure, especially for tissues such as those of the central nervous system, which is composed predominantly of nondividing cells. Until more is known about such effects, HZE particles introduce an added uncertainty into evaluation of risk from this component of the "expected" radiation exposure. Until such time, it is the Panel's feeling that exposures involving high-LET particles should be recorded separately as well as being added into the total dose-equivalent in the manner currently employed.

GENERAL ASSUMPTIONS AND RECOMMENDATIONS

The proposed radiation-protection guides may seem inordinately high in comparison with current guides for terrestrial occupational exposure. They are proposed on the assumptions that (a) they are to be used <u>only</u> for current space-mission and vehicle-design studies; (b) space missions of the next 10 to 20 years will be high-risk operations, and the radiation hazard should be considered realistically and in perspective with other inherent risks; (c) they will be subject to review and revision as additional pertinent information becomes available and before application to actual operations; (d) an active career in earth-orbital operations can be terminated at any time, and careers in deep-space flight can be terminated at the end of any specific mission; (e) the number of people involved will be small and most will be in the older-than-30 age group; (f) participants will be highly motivated volunteers well informed about the nature and extent of the radiation risk; and (g) the agencies concerned appreciate the desirability of keeping exposure as low as practicable by appropriate engineering and operational considerations.

The Panel recommends that (a) both retrospective and prospective studies of radiation effects in man be continued vigorously, (b) further animal studies of dose-rate dependence of radiation induction of neoplasms be considered, (c) attention be given to the possibilities of synergism between radiation and other stresses in the space environment, and (d) the agencies involved in space operations of the next decade or two explore possible facilities for experimentation on HZE particle inactivation cross sections for nondividing cells and the effect of progressive destruction of such cells on the functions of the central nervous system, retina, etc., to provide a basis for evaluation of risk from long-term exposure to this component of galactic radiation.

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APPENDIX A

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS 77058

IN REPLY REFER TO: DC7/11/L137/69

NOV 24 1969

Dr. Herbert G. Shepler
Executive Secretary
Space Science Board
National Academy of Science
Washington, D.C. 20418

Dear ~~Dr. Shepler~~ Herb:

The attached draft, "MSC Suggested Radiation Protection Design Criteria," is submitted for consideration by the Radiobiological Advisory Group during its meetings scheduled for December 4 and 5. The draft results from studies by certain members of our Radiation Constraints Panel after consultation with our space station study contractors and a review of recommendations by the staff at Marshall Space Flight Center. As you probably are aware, it is the responsibility of this Center to establish medical standards for manned space flight for all of NASA.

It is requested that the Radiobiological Advisory Group examine the attached and if possible, provide us with a statement of "reasonableness" if it appears that way from a scientific point of view. If this is not possible, it is hoped that the Group might suggest other criteria which are more correct in their view. In any event, your early review will be appreciated since our engineering studies are currently being slowed materially by the lack of precise radiation shield information.

I want to thank you and the members of the Group for the excellent way in which you have solved some of our most difficult problems in the past. While I was unable to talk with you personally during your last meeting here in Houston, I am assured by my staff that you have begun the new tasks associated with space station and planetary exploration enthusiastically.

Sincerely,

Chuck.

Charles A. Berry, M.D.
Director of Medical
Research and Operations

Enclosure

DRAFT
DC7:CMBarnes:dls
November 21, 1969

MSC - SUGGESTED RADIATION PROTECTION DESIGN CRITERIA

A. DESIGN CRITERIA FOR SPACE STATION/BASE

1.* Reactor Shield Protection such that the dose rate to the crew from this source will not exceed 0.15 rem per day.

2.* Environmental Protection such that the crewmember dose from all environmental radiation (galactic radiation, Van Allen Belt including South Atlantic anomaly radiation, and solar flares) will not exceed 25 rem per year.

* NOTE: These criteria assume a crew stay time within the station/base not to exceed one year in duration. Further, a rest and recuperation period without occupational radiation exposure and of a time equivalent to the duration of the last mission is required prior to receiving additional radiation exposure. The radiation dose is measured at 5 cm tissue depth.

B. DESIGN CRITERIA FOR PLANETARY MISSION SPACECRAFT

1.* Reactor and Nuclear Propulsion System Protection such that the crew dose rate from these sources will not exceed 0.15 rem per day at 5 cm tissue depth.

2.* Environmental Protection such that the crew dose from all environmental radiation (galactic, belt passage, and solar flares) will not exceed 25 rem per year.

* NOTE: These criteria assume planetary missions of three-year duration and extensive rest and recuperation period without significant radiation exposure preflight and postflight. The radiation dose is measured at 5 cm tissue depth.

C. DESIGN CRITERIA FOR ADVANCED LOGISTICS SYSTEMS (SPACE SHUTTLE)

Protection will be provided such that an accumulated dose to the crew from all radiation sources over a period of one-year operation will not exceed 25 rem. This assumes a maximum career as shuttle crewman of ten years. The radiation dose is measured at 5 cm tissue depth.

SPACE NUCLEAR PROPULSION OFFICE

U.S. ATOMIC ENERGY COMMISSION

WASHINGTON, D.C. 20545

Dr. Herbert G. Shepler
Secretariat, National Academy of Sciences (NAS)
2100 Pennsylvania Ave., N.W.
Room 417
Washington, D. C.

NOV 20 1969

Dear Dr. Shepler:

As agreed at the October 29 and 30 meeting of the Radiobiological Advisory Group, Space Science Board, NAS, at Houston, a brief description of the reusable nuclear rocket program is provided here along with the dose criteria currently used in design studies. The rationale behind the criteria is also discussed. I understand that the Radiobiological Advisory Group plans to meet again early in December. Should the Group desire further information, we would be happy to provide it at that time.

The new, post-Apollo space program envisions the development of a reusable nuclear rocket stage for application in two broad manned mission classes:

a. Initially, for shuttling personnel, equipment and supplies between a low Earth orbit and space stations in synchronous Earth orbit, lunar orbits or other high energy orbits.

b. Later, for manned planetary explorations.

Due to the radiation field generated during engine operation, shielding must be provided to reduce energy absorption in the liquid hydrogen propellant and in components located in the engine compartment (see Figure 1 for a schematic for a reusable nuclear stage). In addition to engine shields, the hydrogen propellant screens out most of the remaining gammas and essentially all neutrons except as the tank empties during the last few minutes of the final engine operation. Hence, the flux at the crew/passenger compartment is nearly all from gamma rays. The magnitude of this flux depends in part on the configuration and amount of additional shielding afforded by the equipment bay. In many designs studied to date, an additional crew shield is required. Table 1 lists some preliminary results illustrating how crew shield and total shielding weights vary with the attenuation inherent in the configuration if the crew dose is held to an arbitrary 10 rem per orbit-to-orbit round trip.

For a planetary exploration, the large distance separating the crew and engine compartments plus the shielding afforded by the equipment and stores work together to minimize the need for additional shielding.

Configurations suitable for the orbit-to-orbit shuttle generally require considerable additional crew compartment shielding, however. For a typical Earth orbit to synchronous orbit and return mission, spacecraft shield weights on the order of 3,000 pounds are indicated. Since shielding represents a pound for pound loss in payload, there is considerable incentive to avoid unnecessary penalty due to unrealistic design dose criteria.

To provide for economical space operations, the nuclear stage will be designed for many reuses. Hence, propellant resupply, checkout-out and some maintenance activity is contemplated between each round trip. Thus, in addition to flight crews and passengers, consideration must also be given to maintenance personnel and the shielding required for their protection between flights.

At least three types of dose criteria are recognized: one for purposes of design, one for pre-launch decisions, and a third for deciding whether or not to abort after the mission is in progress. The latter two involve risk-benefit judgments related to the specific mission, mission duration, and vehicle configuration at hand, previously accumulated crew dose, future crew utilization, etc. Dose criteria for design purposes, however, must envision typical or average cases and expected crew utilization schedules. For the reusable nuclear stage, provisional design criteria are based on the orbit-to-orbit application since it is believed to be the more restrictive case. The thinking goes as follows:

a. As a first step, some nominal flight frequency and crew utilization schedule must be envisioned. We have assumed an average of one orbit-to-orbit round trip per month with each mission lasting one month. We further assume that crew members will rotate so an individual will fly no more than four missions per year (with two months rest between flights) for a period of five years, i.e., no more than 20 flights per career. Design criteria must also recognize that there will be departures from the norm. We assume that some flights (or maintenance activities) will result in a dose up to twice the average and that the rest period between missions may occasionally be as short as one month.

b. Next, one must adopt some risk/benefit philosophy. Due to the extraordinary nature of space operations and the unique benefits to be derived, radiation dose levels in excess of those established for radiation workers in ordinary circumstances could undoubtedly be justified. For certain special missions and circumstances, higher doses undoubtedly will be permitted. To provide such flexibility in operational situations, however, and considering the variety of stage configurations and mission uses, design criteria should be reasonably conservative. More specifically, we believe it prudent to design so that flight crews, passengers and maintenance personnel will not be subject to any effect from radiation substantially different from that of radiation workers under normal circumstances. In addition, we certainly want to avoid any early effect which could temporarily impair a crewman's performance and thus increase the possibility of an accident.

c. The NCRP recommendations for radiation workers contemplate an average dose of 5 rem/year over a normal working career. Assuming active work for 40 years, the total career dose would be 200 rem. The Federal Radiation Council agrees with the opinion of the NCRP that this dose of ionizing radiation is not expected to cause appreciable bodily injury to a person at any time during his lifetime.[1] We recognize that this assessment assumes the total dose will be accumulated over a normal working career with no more than 3 rem absorbed in any quarter. After studying the Group's previous report[2] we find no reason to assume that this assessment would be changed in any substantial way even if the total dose is accumulated over an active space flying career as short as five years.

d. Combining this assessment with the crew utilization assumptions of paragraph a, the reusable nuclear stage should be designed to limit the average dose per flight to 200/20 = 10 rem (measured at a depth of 5 cm).

e. For passengers who would not be expected to make more than one or two round trips in a lifetime, somewhat higher doses would be reasonable provided, of course, that acute effects are avoided. Thus, a limit of 20 rem per round trip for infrequent passengers would seem reasonable for the purpose of nuclear stage design criteria.

We would be pleased if the Group could review the bases for these design criteria, especially our understanding of the dose-effect relations of paragraph c, above, and provide us with any comments they may have.

Sincerely yours,

Milton Klein
Manager

cc: Dr. C. M. Barnes, MSC

1/ FRC Report No. 1, May 13, 1960

2/ Radiobiological Factors in Manned Space Flight

FIGURE 1

SCHEMATIC REUSABLE NUCLEAR STAGE

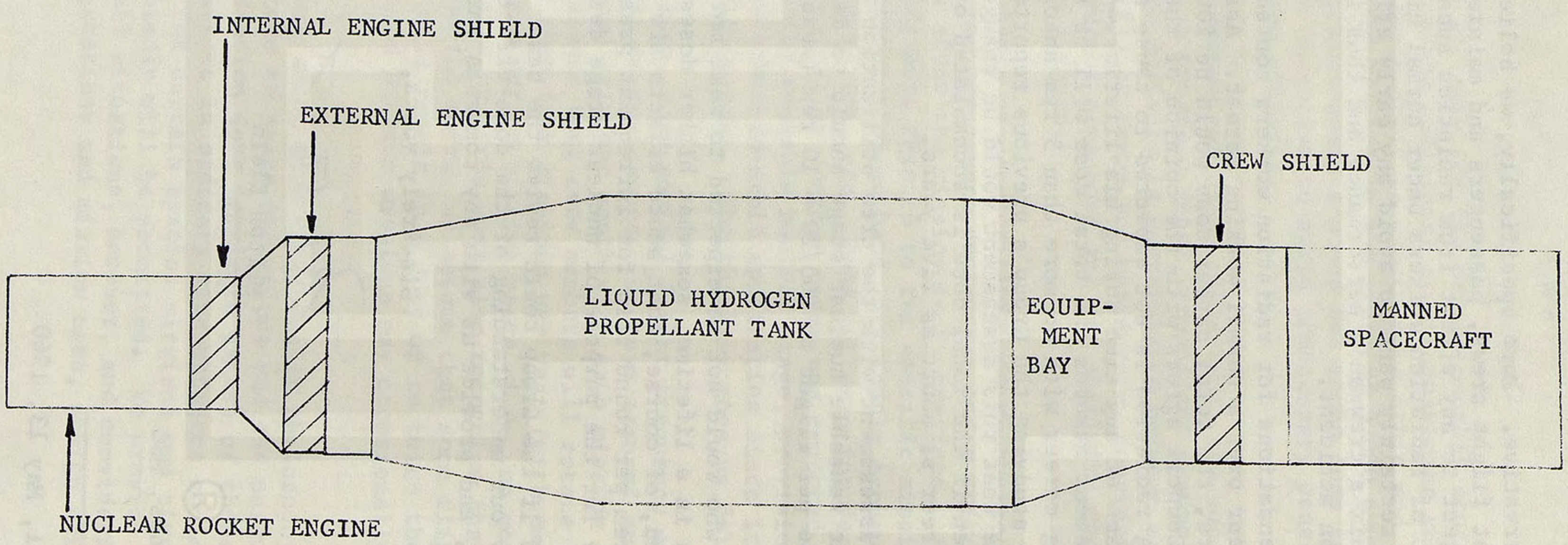

TABLE I

SHIELD WEIGHT FOR CREW DOSE OF 10 REM FOR

TABLE I

SHIELD WEIGHT FOR CREW DOSE OF 10 REM FOR

VARIOUS PAYLOAD ATTENUATION FACTORS

PAYLOAD ATTENUATION FACTOR	SHIELD WEIGHT (LBS)			
	INTERNAL ENGINE SHIELD	EXTERNAL ENGINE SHIELD	SHIELDING AT PAYLOAD	TOTAL
1	3300	10,000	9,000	22,300
3	3300	10,000	3,500	16,800
10	3300	7,300	-	10,600
20	3300	4,400	-	7,700
30	3300	2,900	-	6,200
50	3300	1,300	-	4,600
100	3300	-	-	3,300

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

NOV 25 1969

Dr. Herbert G. Shepler
Secretariat
National Academy of Sciences (NAS)
Room 417
2100 Pennsylvania Avenue, N. W.
Washington, D. C. 20418

Dear Dr. Shepler:

As agreed at the October meeting of the Radiobiological Advisory Group, Space Science Board, NAS, a brief description of the reactor-thermoelectric power system presently under discussion for space station application is forwarded for the group's information.

The planning dose shown in Table 4 evolved from previous planning dose figures used in earlier space application studies such as MORL, Lunar Base, etc. The number selected (100 rem) was a working group solution to establish a planning dose which would be realistic and yet conservative from a long-range effect standpoint. Other than being the result of a group effort, the planning dose used in Table 4 is an assumed value for planning purposes and has no official sanction as an established career/mission limit.

If we can provide the group with additional information, please advise us.

Sincerely yours,

George P. Dix

George P. Dix, Chief
Safety Branch - SEPO
Space Nuclear Systems Division

cc: Dr. Wright Langham, LASL

25 kwe REACTOR-THERMOELECTRIC POWER SYSTEM FOR MANNED ORBITING SPACE STATIONS

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ABSTRACT

A 25 kwe nuclear reactor-thermoelectric power system under design for potential use with NASA's space station in the mid-1970's is described. The integration of the system with the station is also covered using results of a joint study between the AEC and NASA-MSFC.

INTRODUCTION

Plans for NASA space missions in the post-Apollo period include the deployment of large, semipermanent manned space stations operating in low earth orbit. Current trends are to substantially increase the overall size, crew complement, lifetime, functions, and thus the utility of such space stations relative to early orbiting workshops which will be flown in the early 1970's. The space station's electric power requirements are thus expected to increase into the range where nuclear reactor power systems could provide an attractive alternative to solar power systems based on the results of previous studies (1).

In order to help meet potential requirements of this nature, the AEC has been developing and improving the technology base for SNAP reactors and key thermoelectric power conversion system components for several years. As of this writing, the sixth SNAP reactor (S8DR) is operating at Atomics International (AI) in a long term endurance test at 600 kilowatts (thermal). Five previous reactors of this same basic type have successfully demonstrated over 35,000 test hours, and more than 10,000 hours endurance have been demonstrated on all key reactor components.

Work on thermoelectric power conversion components has also progressed significantly in recent years. The Westinghouse Astronuclear Laboratory (WANL) has developed compact, tubular thermoelectric modules using lead telluride (PbTe) which exhibit high efficiency and stable performance at temperatures of interest for a reactor-thermoelectric system. This technology is now sufficiently advanced to permit serious consideration of reactor-thermoelectric systems in the 25 to 50 kwe range for manned or unmanned missions in the mid-1970's. Consequently, in late 1967, the AEC initiated a reactor-thermoelectric system engineering and component development program at AI with WANL as subcontractor. Based on the initial results of this work, a joint power system/spacecraft design and integration study was initiated in mid-1968 by the AEC and NASA, Marshall Space Flight Center (MSFC). The objectives of this study were to define the nuclear reactor-thermoelectric power system's design, performance and operational characteristics, to evolve suitable integration concepts, and to identify potential problem areas and development requirements. AI performed the power system design and analysis work under contract to the AEC, and the integration and mission analysis work was performed in-house by NASA-MSFC.

This paper presents a summary of the results of the joint study, starting with the mission and power system requirements, as estimated by NASA-MSFC in mid-1968. The design and performance characteristics of a reference 25 kwe reactor-thermoelectric power system are then described, after which the integration and operational aspects of the nuclear powered space station are presented. The general characteristics of reactor-thermoelectric power system designs with power outputs up to 50 kwe using the same reactor and technology base as the 25 kwe system, are also included. Finally, the conclusions and recommendations based on the results of this work are presented.

POWER SYSTEM REQUIREMENTS

The design and performance characteristics of most space power systems depend strongly on the mission assumptions, constraints, and requirements. The key requirements affecting the power system design for the NASA space station studied are listed on Table 1.

The desired launch data primarily affects the level of technology upon which the power system design can be based. The two alternate launch modes require that the power plant be configured to fit within the allowable shroud envelopes for both Saturn and Titan class vehicles, weigh less than approximately 32,000 lb, and be fitted with a suitable docking adaptor for attachment and separation from the station.

The crew size has a direct effect on the electrical power requirements, a more detailed breakdown of which is shown on Table 2. The 25 kwe average, unconditioned power requirement is near the upper end of the expected range estimated by MSFC for this 6-man station.

TABLE 1

MISSION ASSUMPTIONS AND POWER SYSTEM REQUIREMENTS

Initial Launch Date	1975
Launch Mode	Integral with space station on 2-stage Saturn V (unmanned) or separate with Saturn 1B or Titan 3M/Transtage (unmanned)
Operational Mode	Zero "g"
Nominal Orbit	270 n. mi, 50° inclination
Payload Limit (for separate launch)	~32,000 lb
Crew Size	6 (9 for short intervals)
Average Power Level	25 kwe (unconditioned)
Voltage	28 vdc (minimum); 42 to 84 vdc desired
Allowable Crew Radiation Dose (Total from Space and Nuclear Power System)	80 rem/6 mo; 100 rem/yr
Design Lifetime	2 yr minimum; 5 yr goal
Reliability	Full power .96; 75% power .98; 20% power .990
End-of-Life Reactor Disposal	Orbit boost to ~450 n. mi or deboost into ocean

TABLE 2

ESTIMATED SPACE STATION POWER REQUIREMENTS

	Watts
Life Support	5,000 - 7,000
Lighting (General)	1,400
Thermal Control	1,200
Attitude Control	1,000 - 3,500
Instrumentation and Communications	1,000 - 3,000
Maintenance, Checkout, Repair	1,000
Airlock/MDA	1,000 - 2,000
CSM (Quiescent) Each	1,000 - 2,000
Experiments (On-Board)	2,000
Docked Remote Modules	1,000 - 3,000
Subtotal	15,600 - 26,100
Contingency 10%	1,600 - 2,600
Total	17,200 - 28,700

The 2 to 5 year lifetime requirement is based on total mission cost considerations, which obviously favor longer subsystem lifetimes for semi-permanent space stations. The reliability goals reflect a desire for high partial power as well as full power reliability, a factor which influences the redundancy and/or modularity incorporated in the design of the power conversion system.

The assumed allowable crew radiation dose is based on recommendations made in previous studies (2), and is roughly consistent with the 55 rem limit set by NASA (3) for the shorter duration Apollo mission several years ago. Finally, it was assumed that end-of-life reactor disposal provisions would be required to satisfy nuclear safety requirements, since the 7 to 15 year orbital decay period from the 270 n. mi orbit would not be long enough to permit sufficient decay of long-lived fission products produced during reactor operation.

POWER SYSTEM DESIGN AND PERFORMANCE

The reference 25 kwe power system design evolved to meet the above requirements consists of a zirconium hydride-type nuclear reactor coupled to four parallel thermoelectric power conversion sections as shown in Figure 1. Each of the four independent power conversion sections includes a 6.3 kwe thermoelectric converter assembly, a heat rejection loop (HRL) and a pump assembly which circulates the liquid metal (NaK) coolant in both the primary and heat rejection loops. Heat is transferred from the reactor to the hot side of the tubular, PbTe converter assemblies via the primary coolant loop at an average temperature of 1145°F at design operating conditions. The waste heat is rejected from the cold side of the converter at an average temperature of 563°F. The temperature differential across the TE converters produces the 25 kwe power at an overall system efficiency of 4.3%. The system contains no moving parts, valves, or controls other than those required for the reactor.

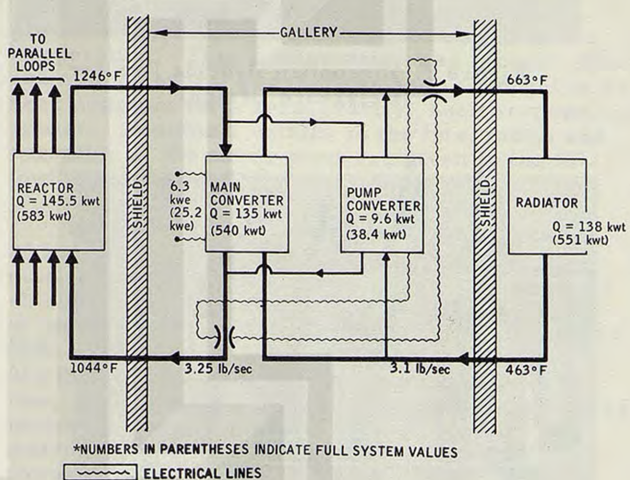


Figure 1. ZrH Reactor-Thermoelectric System Schematic

The reactor design is similar to the SNAP 8 reactor which is currently on test, but has a slightly larger core and an internally cooled reflector suitable for operation within an enclosed shield. Figure 2 shows a cutaway illustration of this design, which is currently being developed at AI under the AEC's Zirconium Hydride Reactor Program. Ten cylindrical BeO control drums with neutron absorbing material on one side are installed in dry wells, the outer surface of which are cooled by the NaK which enters the bottom annular plenum through four inlet nozzles. The NaK flows upwards around the dry wells and fixed reflector elements into the upper plenum, downward through the core to the lower plenum and out through four exit nozzles.

The estimated performance capabilities of the reference ZrH reactor are shown on Figure 3. The reactor lifetime (as limited by reactivity and/or fuel element swelling) is dependent on the thermal power and operating temperature. The limits shown are not the threshold for a sudden loss of power, but rather mark the probable beginning of a gradual reduction in temperature and power.

The thermoelectric converter assembly, shown on Figure 4, consists of 24 tubular, lead telluride modules structurally supported within a rectangular box and interconnected with coolant manifolds for proper flow distribution of the hot primary loop and the cold HRL. The tubular modules are arranged in six parallel 4-packs, each of which produces slightly more than 1 kilowatt at design operating conditions. TE modules of this type are currently on test at WANL and at AI and testing of similar modules has accumulated more than 300,000 hours, with the longest single module test now exceeding 30,000 hours.

The four NaK pumps, one of which is shown on Figure 5, are of the dc-conduction electromagnetic (EM) type. Each pump has two separate

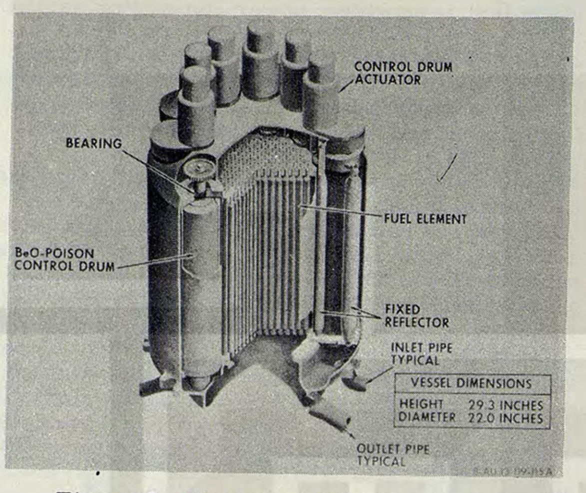


Figure 2. Zirconium Hydride Reactor (Reference Design)

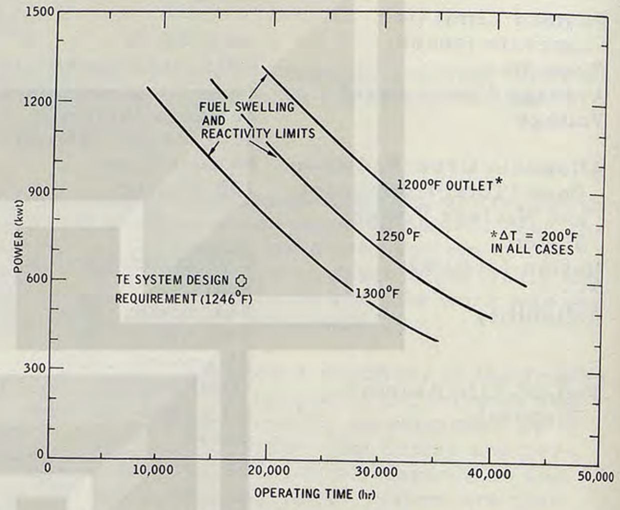
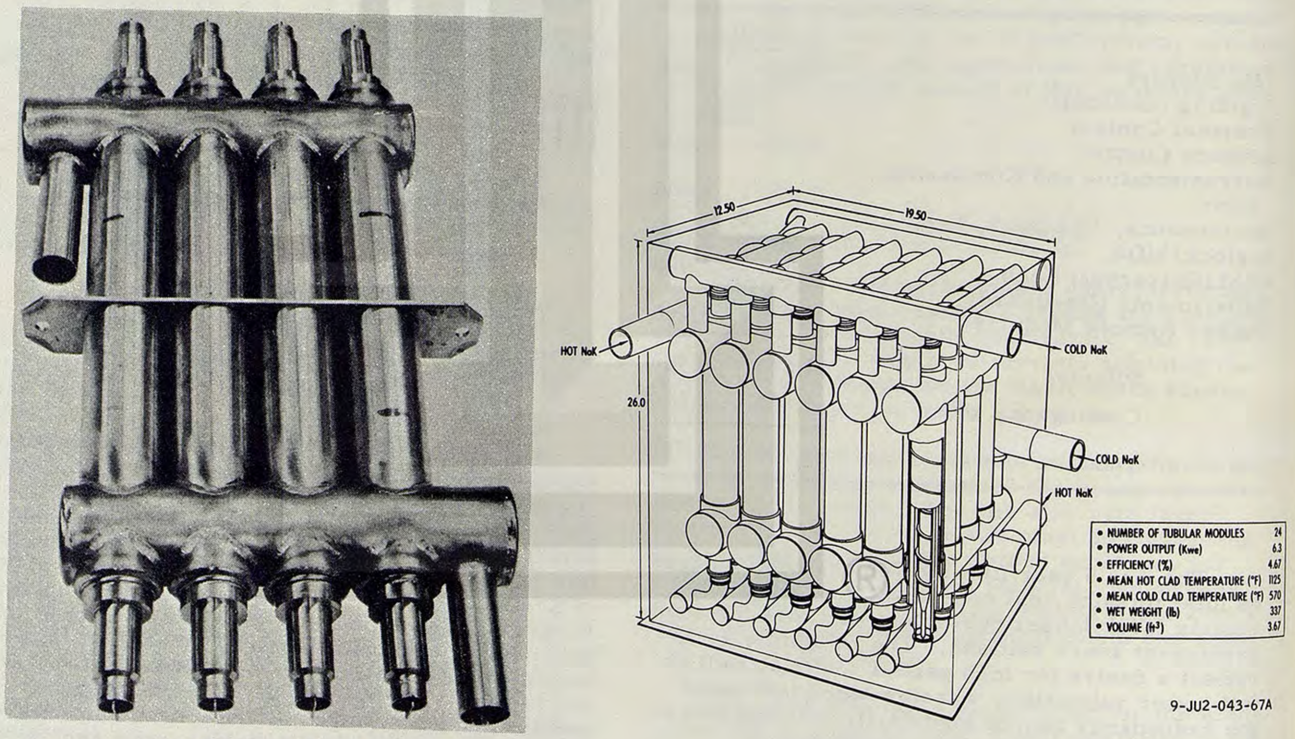


Figure 3. Performance Map – Reference ZrH Reactor



4-PACK ASSEMBLY MOCKUP

Figure 4. Converter Module

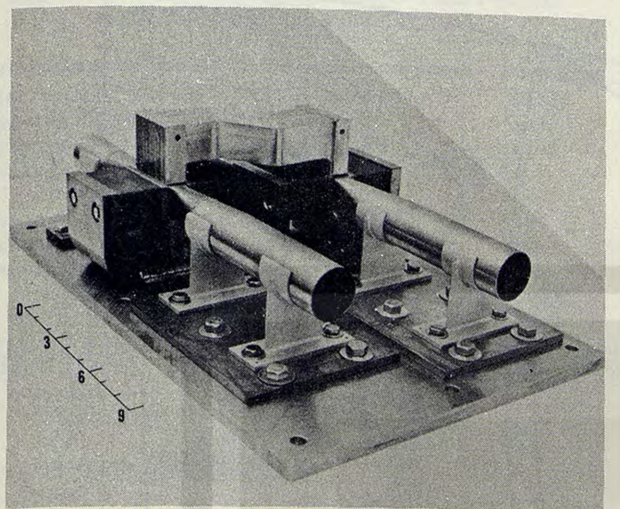


Figure 5. NaK Pump

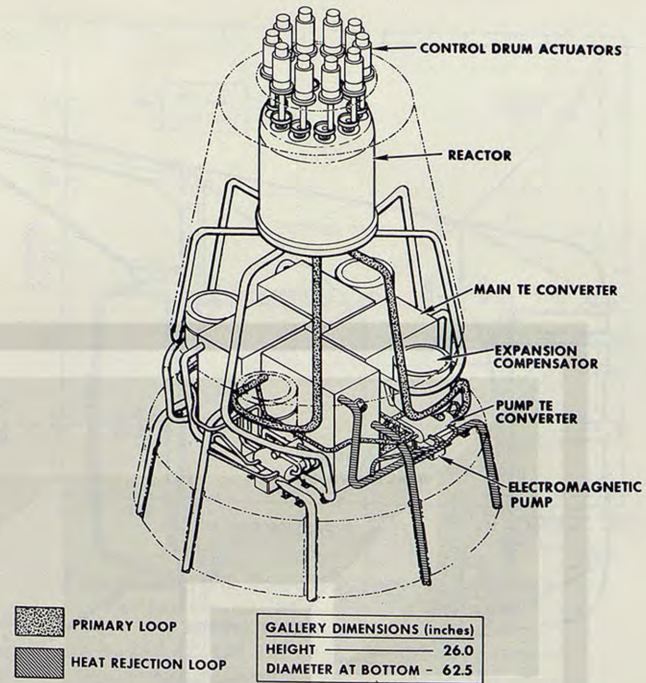


Figure 6. ZrH Reactor-Thermoelectric System (Reactor/Gallery Arrangement)

throats; one circulates one-fourth of the primary loop flow and the other pumps one of the four separate heat rejection loops. A separate thermoelectric power pack consisting of three high current TE modules connected in parallel provides the dc power to each pump assembly. High-current TE pump modules are currently on test and the prototype pump assembly shown on Figure 5 is being assembled for test as of this writing. Similar pumps developed under previous SNAP programs have exceeded 20,000 hours of endurance testing and accumulated over 200,000 pump hours.

The arrangement of the reactor and power conversion components for the space station power plant is as shown on Figure 6, which also shows the outline of the radiation shield in phantom. The PCS components are compactly packaged within a gallery between the two halves of the split shield. This arrangement is required to provide gamma shielding between the radioactive primary NaK loop and the space station.

Figure 7 shows a cross-section through the weight-optimized radiation shield designed to meet the requirements of this mission. The gamma shielding materials are lead, tungsten, and depleted uranium; lithium hydride is used for neutron shielding. The shield is thickest in the direction of the space station where the crew will spend 99% of its time. The side shield thickness and geometry is designed to limit the dose accumulated during rendezvous operations to acceptable levels with the reactor operating at full power. Further details on the shield performance are discussed in subsequent sections of this paper.

The overall layout of the reference, 25 kwe power system, including the radiator is shown on Figure 8. The radiator design is of conventional fin and tube geometry, with stainless steel NaK tubes diffusion bonded to aluminum fins and meteoroid armor. The radiator panels are mounted on a titanium inner structure similar to that used on SNAP 10A.

Figure 9 shows how the power system integrated with the space station would appear while in operation. This configuration was evolved after examining several alternatives and is thought to be near optimum for a zero-gravity, nuclear-powered station. Additional details on the integration and operation of the power plant are given in the following section of this paper.

The salient characteristics of the reference, 25 kwe reactor-thermoelectric system are summarized in Table 3. It will be noted that the total shielded system weight is approximately 22,230 lb, of which the radiation shield constitutes more than 60%. The specific weight is thus approximately 884 lb/kwe, shielded, and approximately 326 lb/kwe, unshielded. Other significant characteristics include a specific area of 55 ft^2/kwe and an estimated lifetime of approximately 4 years at rated power.

Although this design represents a unique design point which is believed to be near-optimum, numerous trade-offs between system weight, area, efficiency, temperature, power level, and lifetime are possible. Similarly, a fixed system can be operated at off-design conditions with reduced power outputs, as shown on Figure 10 by merely operating the reactor at reduced power and temperature. This mode of operation may be desirable for a space station whose size and functions are expected to grow in time.

SPACE STATION DESCRIPTION AND OPERATION

The orbital configuration of the space station is shown in Figures 9 and 11. The design of this station evolved from the Intermediate Orbital Workshop design established in a previous study by NASA-MSFC.

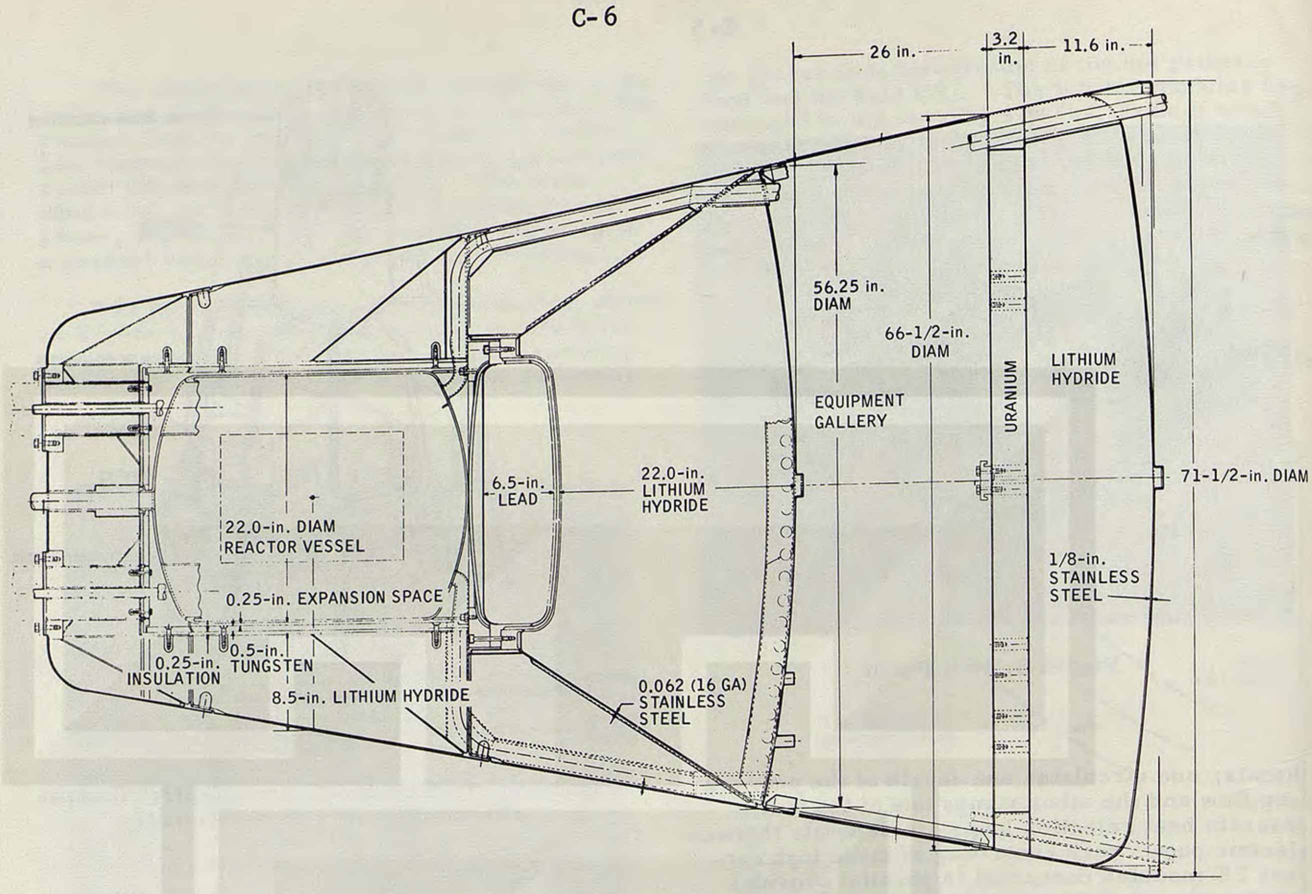


Figure 7. 4π Shield with Structure

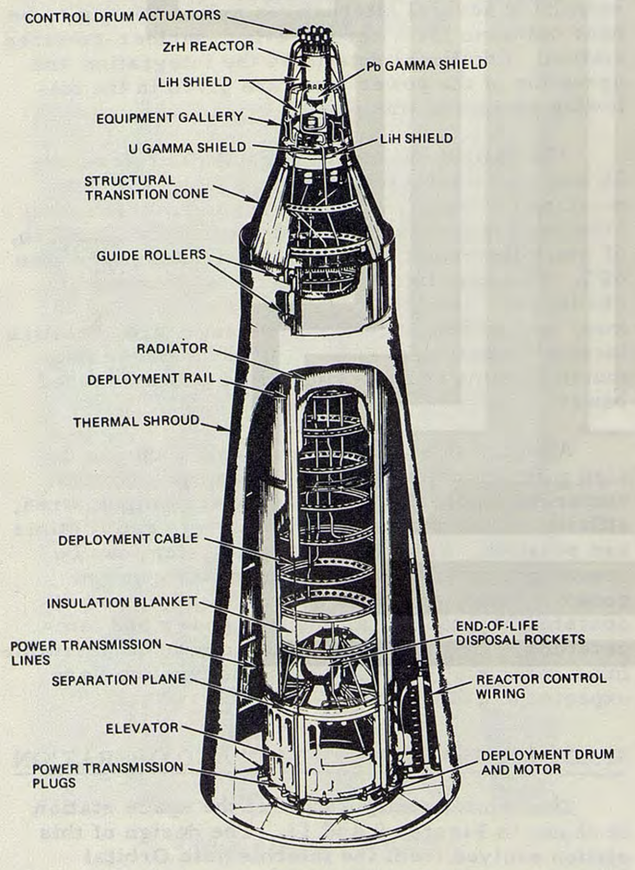


Figure 8. Reactor-Thermoelectric Power System

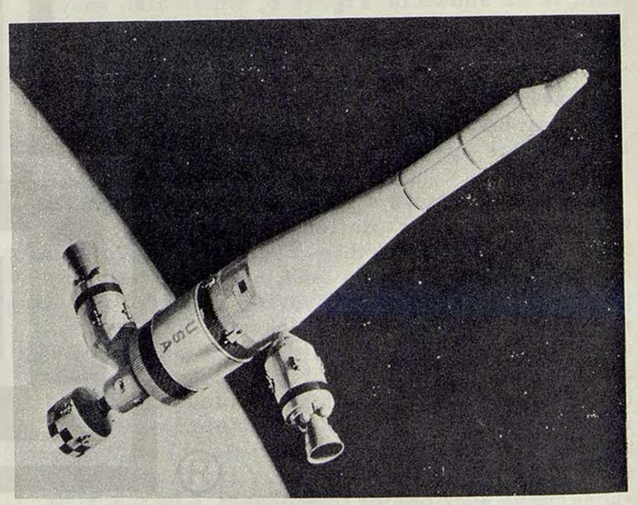


Figure 9. Space Station in Orbit

TABLE 3

REFERENCE 25 kwe REACTOR-TE SYSTEM DESIGN AND PERFORMANCE CHARACTERISTICS

Electrical Power (Unconditioned) (kwe)		25.3
Reactor Power (kwt)		583
Reactor Outlet Temperature (°F)		1246
Average TE Converter Hot Clad Temperature (°F)		1125
Average Radiator Temperature (°F)		563
Net System Efficiency (%)		4.3
Radiator Area (ft^2)		
(Prime)		1160
(Effective)		1390
Specific Area (ft^2/kwe)		55
Weight (lb)		22,230
Reactor	1,830	
TE Converters	1,350	
Pumps	410	
Expansion Compensators	210	
Piping	950	
Radiator	1,430	
Structure	1,210	
Electrical Wiring	830	
Radiation Shield	14,010	
Specific Weight (lb/kwe)		
(Shielded)		884
(Unshielded)		326
Lifetime (yr)		~4

The nuclear power system is extended out from one end of the space station to provide a suitable separation distance between the reactor and the station and to minimize the angle subtended by the area requiring primary shielding. The effective separation distance between the reactor and the crew quarters is approximately 117 ft. The radiator dimensions were established after studying the tradeoffs between separation distance, shield weight, launch height, and vehicle side projected area. If a longer, smaller diameter radiator was used, the separation distance would be increased and shield weight decreased; however, the launch height and adverse effect of wind on the launch vehicle would be increased. The radiator length selected was somewhat shorter than that resulting in a minimum weight system,

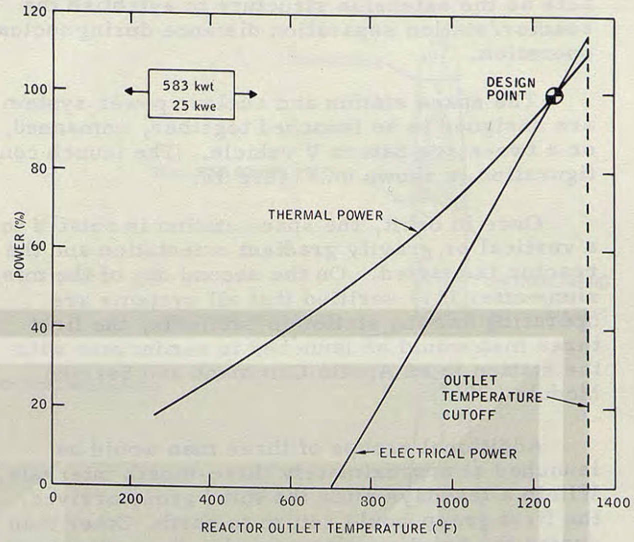


Figure 10. TE Power System Off-Design Performance (at Constant Voltage)

and was based on the largest reasonable launch height for a replacement system launched on a Titan III-F.

The nuclear power system can be moved in and out of a thermal/structural shroud on a deployment elevator. The system is guided by rollers on the shroud that engage rails in the elevator and radiator. The elevator is moved by drums attached to it that "crawl" along stationary cables fixed to the shroud.

The thermal/structural shroud serves three purposes. First, it is the structure that supports the reactor and shield during launch and protects the radiator from aerodynamic loads. During launch, the shroud is attached to the aft end of the transition cone between the radiator and lower shield. It is separated at this point by firing of pyrotechnic devices once orbit is achieved. Second, it is a heat shield that prevents the NaK from freezing during prestart and nonoperating periods. With the NaK circulating at about 3% flow, solar heating on the shroud, even in the worst sun-shade orbital conditions, will maintain the minimum NaK temperature above about 75°F. Finally, the shroud

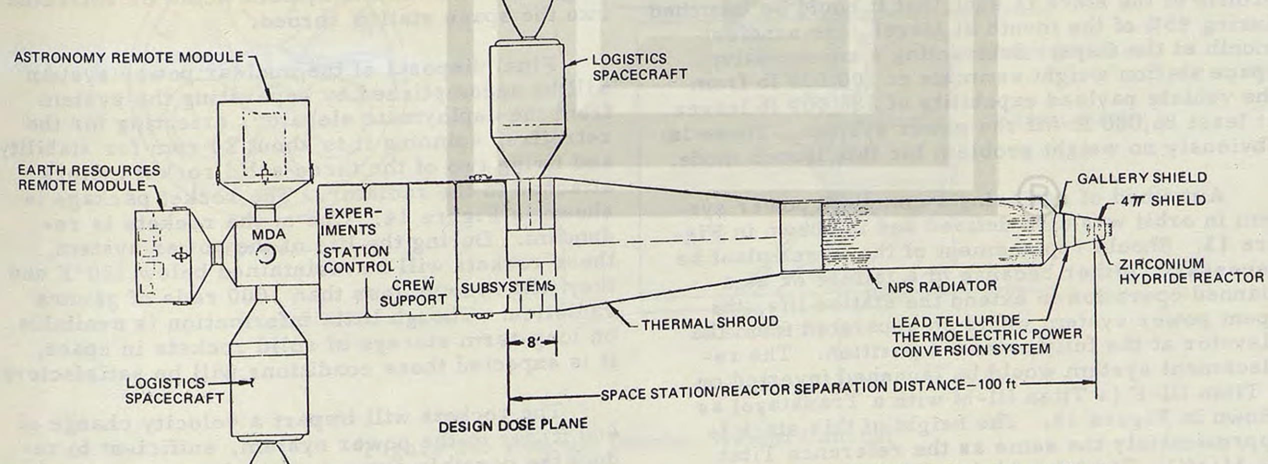


Figure 11. Orbital Configuration

acts as the extension structure to establish the reactor/station separation distance during nuclear operation.

The space station and nuclear power system are designed to be launched together, unmanned, on a two-stage Saturn V vehicle. The launch configuration is shown on Figure 12.

Once in orbit, the space station is rotated to a vertical or gravity gradient orientation and the reactor is started. On the second day of the mission, after it is verified that all systems are operating and the station is habitable, the first three men would be launched to rendezvous with the station in an Apollo Command and Service Module (CSM).

Additional groups of three men would be launched at approximately three-month intervals. Within a few days after the third group arrived, the first group would return to earth. Other than during the brief overlap periods, then, the station would be occupied by six men. Each three-man crew would bring a logistics module or a new experiment module with it. After docking this module, they would disconnect their CSM and move to another docking port so they could enter the station.

The remote experiment modules would be checked while attached to the station and then moved to a position in the same orbit as the space station but preceding or following it by a few miles. This might be accomplished unmanned or it could be done using the CSM as a tug. Throughout the mission, the remote modules would be periodically returned to the station for retrieval of film, etc., checkout and minor maintenance.

Operation of the space station in a gravity gradient stabilized mode with the x-axis pointing toward the earth was selected after examining numerous alternate attitude control methods and orientations. In addition to being the simplest and lightest approach, the gravity gradient mode provides a significant reliability advantage, since it is inherently stable even with the control moment gyro system inoperative.

In the launch configuration, with the space station replacing the S-IVB stage, the total stack is several feet shorter than the standard Apollo with the launch escape tower. The side-projected profile of the stack is such that it could be launched during 95% of the month of March, the windiest month at the Cape. Subtracting a conservative space station weight estimate of 100,000 lb from the vehicle payload capability of 186,000 lb leaves at least 86,000 lb for the power system. There is obviously no weight problem for this launch mode.

A method of replacing a complete power system in orbit was also defined and is shown in Figure 13. Should replacement of the power plant be necessary, either because of a failure or as a planned operation to extend the station life, the spent power system would be separated from the elevator at the fully extended position. The replacement system would be launched inverted on a Titan III-F (a Titan III-M with a Transtage) as shown in Figure 13. The height of this stack is approximately the same as the reference Titan III-M/MOL Gemini vehicle. The Martin Marietta

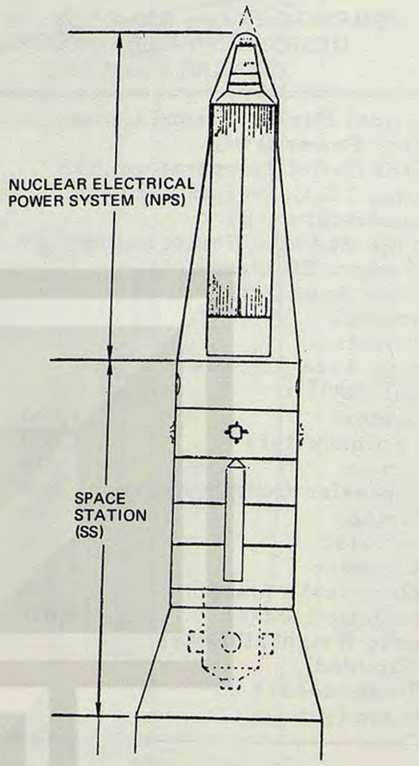


Figure 12. Launch Configuration

Corporation analyzed the configuration and found that 32,200 lb could be placed in the 270 n. mi, 50° inclination orbit. In this analysis, the maximum dynamic pressure was constrained because of the size of the payload fairing. The estimated weight of the payload, including the power system, shroud, nose cone, structural adaptor, end-of-life disposal rockets and docking mechanism, is approximately 32,000 lb.

The Transtage would be used to achieve an unmanned rendezvous and the new power system would be docked into the extended elevator. A thermal/aerodynamic shroud surrounding the radiator would be jettisoned during the initial startup of the new power system, but for subsequent shutdowns the system would be retracted into the space station shroud.

Final disposal of the nuclear power system will be accomplished by separating the system from the deployment elevator, orienting for the retrofire, spinning it to about 20 rpm for stability and firing two of the three solid rocket motors attached to the radiator. The rocket package is shown in Figure 14. One of the rockets is redundant. During the life of the power system, these rockets will be maintained below 150°F and they will receive less than 1000 rads of gamma radiation. Though little information is available on long-term storage of solid rockets in space, it is expected these conditions will be satisfactory.

The rockets will impart a velocity change of 600 ft/sec to the power system, sufficient to reduce the possible error in splashdown print to less than ±60 n. mi. This is extremely conservative

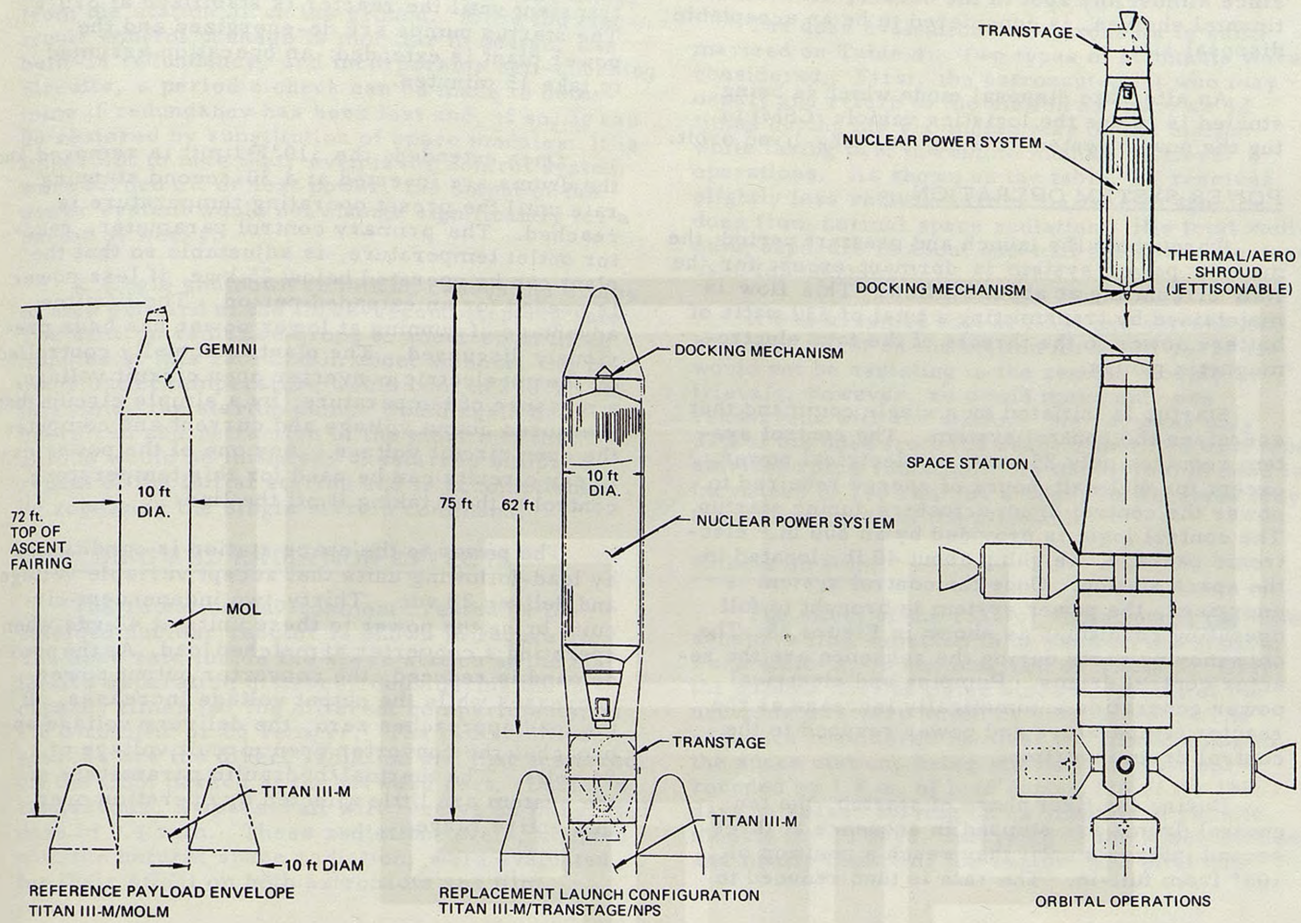


Figure 13. NPS Replacement Launch Mode Unmanned Rendezvous and Docking

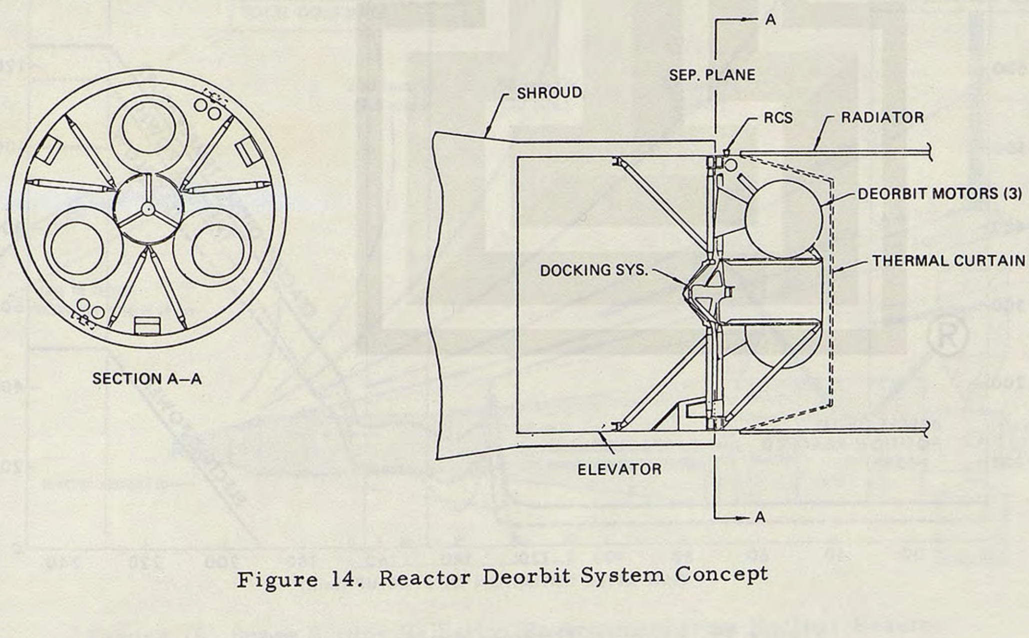


Figure 14. Reactor Deorbit System Concept

since almost any spot in the oceans, off the continental shelves, is considered to be an acceptable disposal site.

An alternate disposal mode which is being studied is to use the logistics vehicle (CSM) to tug the power system to a higher, long-lived orbit.

POWER SYSTEM OPERATION

Throughout the launch and prestart period, the nuclear power system is dormant except for the NaK circulating at about 5% flow. This flow is maintained by transmitting a total of 330 watts of battery power to the throats of the four electromagnetic pumps.

Startup is initiated by a single command that energizes the control system. The control system requires only 85 watts of electrical power except for 400 watt-hours of energy required to power the control drum actuators during startup. The control logic is provided by an 800 $in.^3$ electronic package, weighing about 40 lb, located in the space station. Once the control system is energized, the power system is brought to full operating conditions as shown in Figure 15. The only moving parts during the sequence are the reactor control drums. Pumping and electrical power generation automatically increase as the reactor temperature and power respond to the control drum insertion.

During the first phase of startup, the ten control drums are stepped in sequence at three-second intervals until they reach a position of 105° from full-in. The rate is then reduced to one step each 150 seconds through the first transient until the reactor is stabilized at 310°F. The startup pumps are de-energized and the power plant is extended; an operation assumed to take 15 minutes.

Once extended, the 310°F limit is removed and the drums are inserted at a 30-second stepping rate until the preset operating temperature is reached. The primary control parameter, reactor outlet temperature, is adjustable so that the plant can be operated below 25 kwe, if less power is needed for an extended period. The lifetime advantage of running at lower power has been previously discussed. The plant is actually controlled on thermoelectric converter open circuit voltage, a measure of temperature, by a simple circuit that measures output voltage and current and computes the open circuit voltage. Any one of the power delivery circuits can be used for this temperature control without taking it off the line.

The power to the space station is conditioned by load-following units that accept variable voltage and deliver 28 vdc. Thirty-two independent circuits bring the power to these units at 42 vdc when operating a converter at matched load. As the power demand is reduced, the converter output power decreases while the output voltage increases. If the load approaches zero, the delivery voltage approaches the converter open circuit voltage of 84 volts. The thermal/hydraulic parameters of the system are little affected by operation over this entire range.

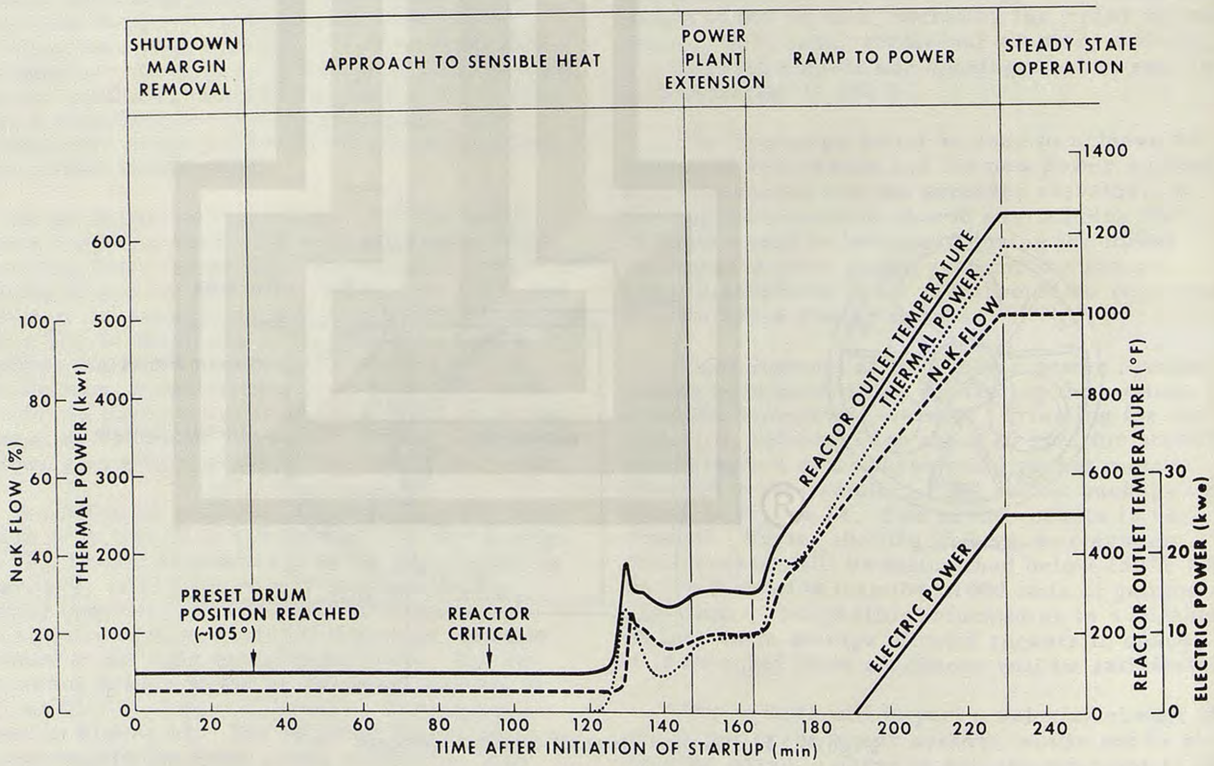


Figure 15. Reactor-Thermoelectric System Startup

During operation, only very limited monitoring of the plant is required and this can be done either from the station or on the ground. Since the electronic control package is modular in design, has built-in redundancy, and incorporates self-checking circuits, a periodic check can be made to determine if redundancy has been lost and, if so, it can be restored by substitution of spare modules. It is important to note that, even if the control system were turned off or lost power, the output of the power system would not change significantly for a period of weeks.

A single shutdown command causes the drums to step outward at the three-second stepping rate. The neutron radiation drops to about 1% in three minutes at this rate and in about an hour, the reactor outlet temperature would cool to 290°F. At this time, the startup pumps would again be energized and retraction of the plant into the shroud would be initiated. Restart is simply a repeat of the initial startup and is accomplished by repeating the single startup command.

SHIELDING AND RADIATION EFFECTS

The radiation environment created by the shielded nuclear reactor is shown in Figure 16. The dose rate inside the space station at the effective separation distance, considering the occupancy times for the different compartments, is 2.8 mrem/hr or 25 rem/yr. The two significant sources are the direct radiation and that scattered off the CSM parked at the forward port. During a rendezvous, a spacecraft will receive an integrated dose of 0.4 rem. These radiation levels, coupled with the natural space radiation, were evaluated for their effect on both astronauts and film.

Effects on Astronauts

The dose evaluation for astronauts is summarized on Table 4. Two types of atronauts were considered. First, the astronaut-pilot who may depart and return to the station as many as 12 times during his six-month stay on the station while taking part in remote module retrieval operations. As shown on the table, he receives slightly less radiation from the reactor than he does from normal space radiation. His total radiation exposure is about one-half the allowable dose used for planning.

It was assumed that at least one astronaut-scientist might on the station for a full year. He would not be assisting in the remote module retrievals, however, so would make only one rendezvous with the station. He receives only 37% of his dose from the reactor and 73% of it from ambient space radiation. As the allowable dose is increased to 100 rem for a year, he receives only about two-thirds of the allowable.

Effects on Film

The effect of the reactor radiation on the most sensitive film expected to be used on the station, Panatomic-X, is summarized on Table 5. Only the gamma dose is listed since the effect of the neutrons was very small by comparison. The sequence considered involves the film coming to the space station, being stored in a vault surrounded by 1.8 in. of lead during 120 of its 180 days in space, staying on an unshielded remote module for 60 days, returning to the space station and finally departing for earth. The effective

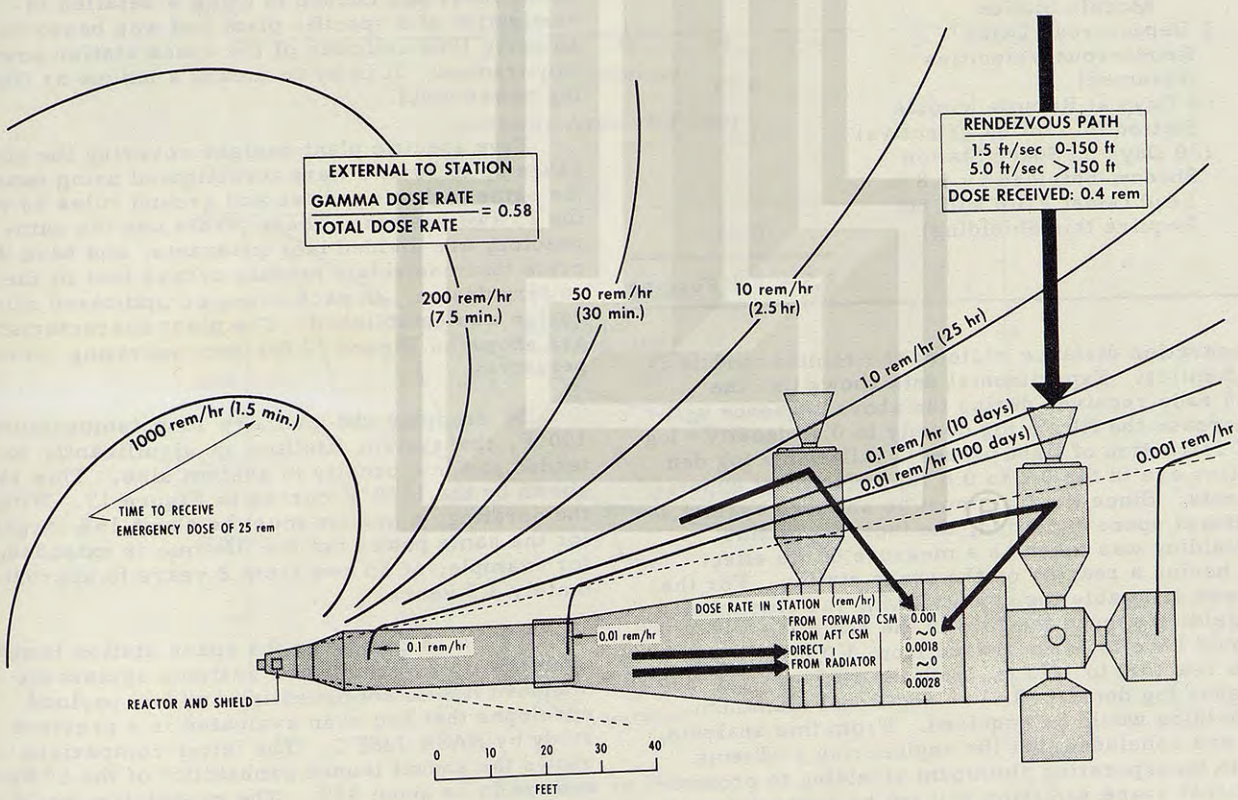


Figure 16. Space Station Radiation Environment from Nuclear Reactor

TABLE 4

ASTRONAUT RADIATION DOSE EVALUATION

	Radiation (rem)			
	Reactor	Space	Total	
Astronaut-Pilot				
13 Rendezvous	5.2	2.0	7.2	
1 Arrival				
12 Returns from Remote Module Station				
13 Departures (Twice Rendezvous Velocities Assumed)	2.6		2.6	
180 Days on Space Station	12.5	22.0	34.5	"Planning"
	20.3	24.0	44.3	80
Astronaut-Scientist				
1 Arrival Rendezvous	0.4		0.4	
1 Departure	0.2		0.2	
360 Days on Space Station	25.0	44.0	69.0	"Planning"
	25.6	44.0	69.6	100

TABLE 5

FILM RADIATION DOSE EVALUATION
Most Sensitive Film Programmed
(Panatomic-X)

Radiation from Reactor	Gamma Dose from Reactor (rads)
2 Rendezvous	0.5
1 Arrival	
1 Return from Remote Module Station	
2 Departures (Twice Rendezvous Velocities Assumed)	0.25
60 Days at Remote Module Station (5.5 miles Effective)	1.5
120 Days on Space Station Shadow-Shielded by 1.8 in. Lead (Most Film will not Require this Shielding)	0.25
	2.5 → 0.1 Fogging

separation distance while on the remote module is 5.5 miles. Experimental data shows that the 2.5 rads received during the above sequence will increase the film's fog density to 0.1 (density = log of 1/fraction of light passed). Allowable fog densities are in the 0.2 to 0.6 range for most experiments. Since the film must be shielded against natural space radiation, the increase in this shielding was taken as a measure of the effect of having a reactor on the space station. For the lower allowable fog density (0.2), the aluminum shielding around the film in the remote module would have to be increased from 1.0 in. (without the reactor) to 1.73 in. (with the reactor). At the higher fog density (0.6) no additional aluminum shielding would be required. From this analysis, it was concluded that the engineering problems with incorporating aluminum shielding to protect against space radiation will not be appreciably different with a reactor on the space station.

The above discussion has been for Panatomic-X. Most other films, particularly those for photographing the earth, will be much less sensitive and will not require the lead shielding on the station.

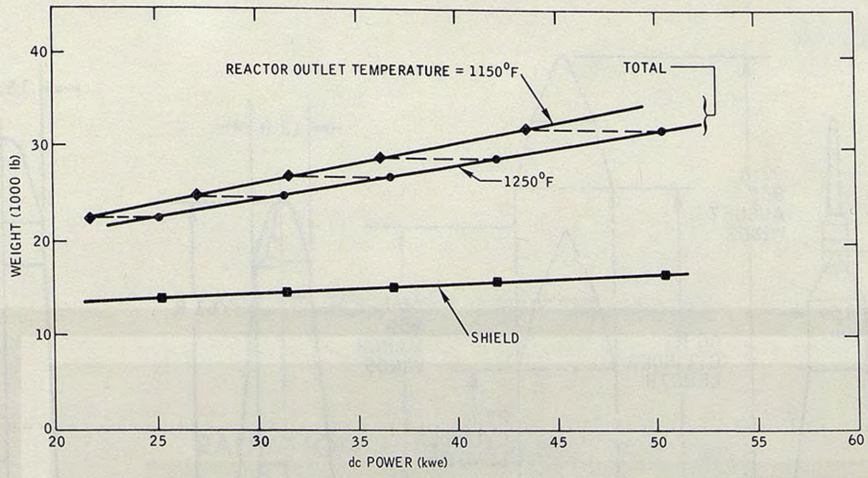
THERMOELECTRIC SYSTEM POWER RANGE

The foregoing discussions have all been related to a 25-kwe thermoelectric system. This power level was chosen to allow a detailed investigation of a specific plant and was based on an early 1968 estimate of the space station power requirement. It is by no means a unique or limiting power level.

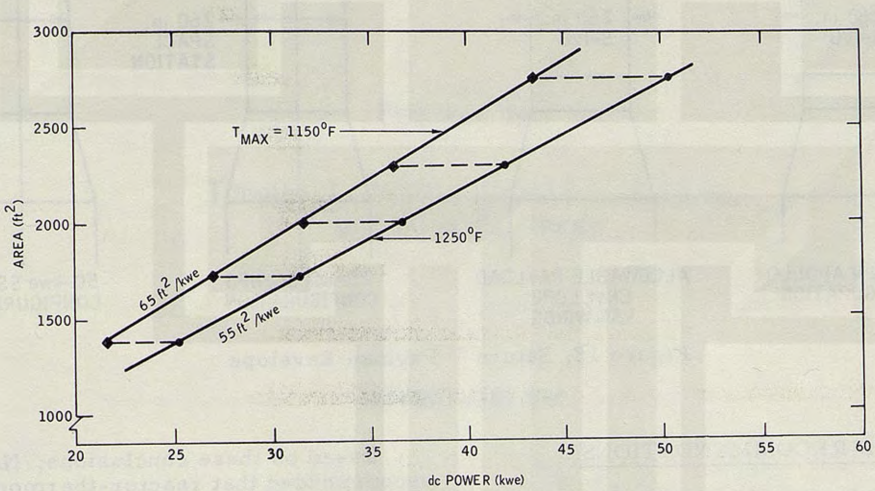
Five specific plant designs covering the power range up to 50 kwe were investigated using exactly the same technology base and ground rules as with the 25 kwe system. These plants use the same reactor, are divided into quadrants, and have discrete thermoelectric module arrays that fit the gallery design. In each case, an optimized shield design was established. The plant characteristics are shown on Figure 17 for two operating temperatures.

By dropping the primary loop temperature 100°F, the system lifetime is significantly extended at some penalty in system size. This is shown by the 1150°F curves in Figure 17. With the derating, a system must be about 15% larger for the same power but the lifetime is extended, for example, at 50 kwe from 2 years to approximately 3.5 years.

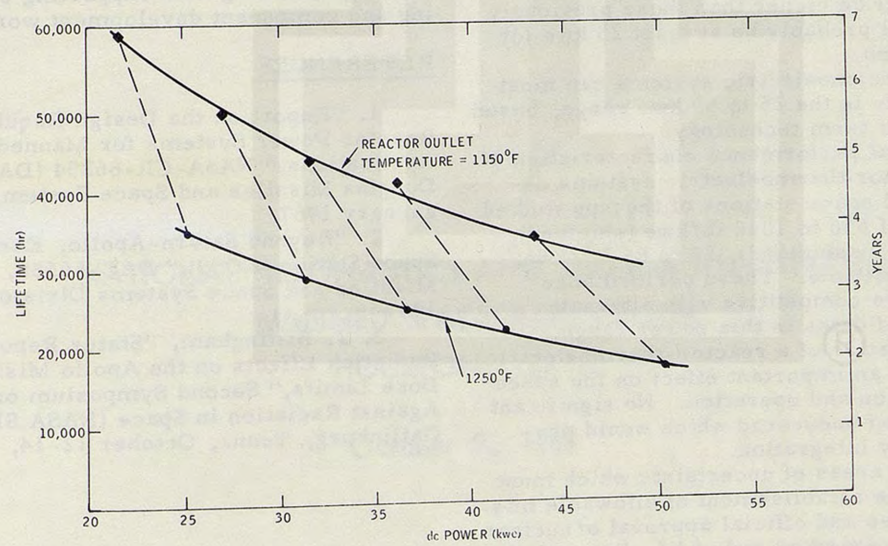
Figure 18 compares the space station launch vehicle with 25 and 50 kwe systems against the standard Apollo configuration and two payload envelopes that had been evaluated in a previous study by NASA-MSFC. The latter comparison shows the annual launch probability of the 50 kwe system to be about 95%. The probability would be less during the windiest month, March, and higher during the least windy month, August.



Shielded System Weight vs Power



Radiator Area vs Power



Lifetime vs Power

Figure 17. Thermoelectric System Characteristics vs Power Level

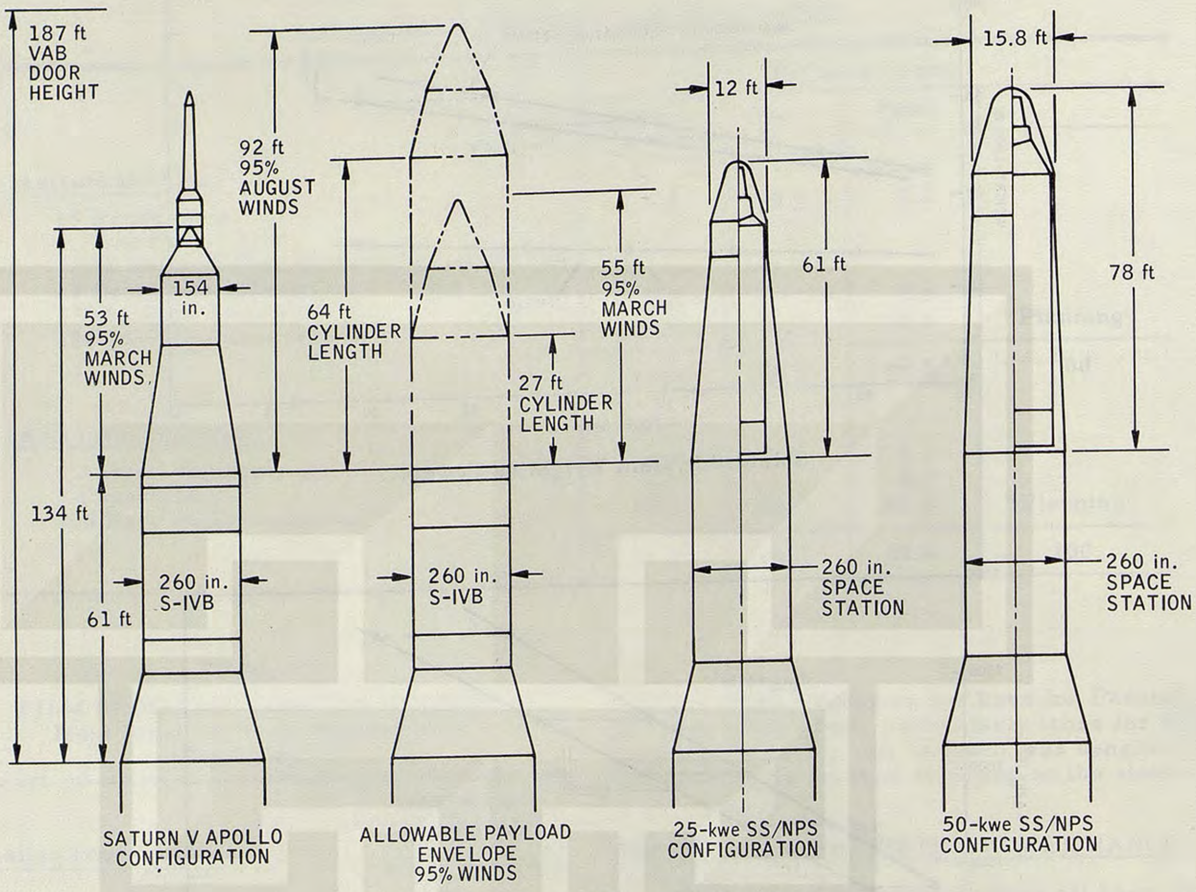


Figure 18. Saturn V Payload Envelope

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions derived from this study and from previous and on-going development programs are as follows:

1) Average power requirements for future space stations will be higher than those previously estimated and will probably be at least 25 kwe for a 6 to 9 man station.

2) Reactor-thermoelectric systems can meet the power demands in the 25 to 50 kwe range, based on current or near term technology.

3) The general performance characteristics of 25 to 50 kwe reactor-thermoelectric systems designed for manned space stations of the type studied are in the range of 630 to 1040 lb/kwe (shielded), 305 to 380 lb/kwe (unshielded), 55 to 65 ft^2/kwe, and 3 to 5 years lifetime. These performance characteristics are competitive with alternate power system candidates in this power range.

4) The integration of a reactor-thermoelectric power system has an important effect on the space station configuration and operation. No significant problems have been uncovered which would prohibit a satisfactory integration.

5) The major areas of uncertainty which must be resolved are the establishment of allowable mission radiation doses and official approval of nuclear safety provisions regarding end of life disposal of the reactor.

Based on these conclusions, NASA-MSFC has recommended that reactor-thermoelectric systems be included as a candidate for the mid-1970 space station through the next phase of studies, and the AEC has implemented the required safety studies and is proceeding with supporting system engineering and component development work.

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MSC DOCUMENT NO. MSC-00183

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HOUSTON, TEXAS

October 9, 1969

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INTRODUCTION

The radiation environments which are "expected" to be encountered by the 1975-1985 space station and space base missions consist of galactic cosmic radiation, radiation produced by onboard, nuclear reactor power generators, and radiation trapped in the earth's magnetic field. The "unexpected" radiation environment which may be encountered consists of solar particle events and high altitude nuclear events. The earth-orbit missions for which data on these environments are presented are a 270 nautical mile, 55° inclination orbit, a 200 nautical mile, polar orbit and an equatorial, synchronous orbit.

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SECTION I: "EXPECTED" RADIATION ENVIRONMENT

The "expected" radiation environments which will be encountered by the 1975-1985 space station and space base missions consist of the galactic cosmic radiation, the radiation produced by the onboard nuclear reactor power generator, and the earth's trapped radiation. These "expected" environments are ones which can be predicted with a reasonable degree of certainty.

Galactic Cosmic Radiation

Galactic cosmic radiation consists of low intensity, extremely high-energy charged particles. These particles, about 85% protons, 13% alphas, and the remainder heavier nuclei, bombard the solar system from all directions. These particles may have energies from 10^8 to 10^{19} electron volts (ev) per particle and are encountered essentially everywhere in space. The intensity of this environment in "free space", e.g., outside the influence of the earth's magnetic field, is relatively constant (.2 to .4 particles per square centimeter per steradian per second) except during periods of enhanced solar activity when the fluxes of cosmic rays have been observed to decrease. This decrease is due to an increase in the strength of the interplanetary magnetic field which acts as a shield to incoming particles. Near the earth, cosmic rays are similarly influenced by the earth's magnetic field resulting in a spatial variation in their intensity (Figure 1).

Estimates of the daily cosmic ray dose for the various orbits are shown in the following table.

Galactic Cosmic Ray Dose Rates (rem/day)			
	270 n.mi., 55° incl.	200 n.mi., polar	Synchronous
Solar Maximum	.005	.008	.024
Solar Minimum	.008	.013	.036

The dose estimates for the low altitude orbits were obtained by merging the trajectory information with the data shown in Figure 1. The synchronous orbit, cosmic ray dose rates were assumed to be the same as the interplanetary cosmic ray dose rates estimated from data obtained on Apollo lunar missions. The variation of the galactic cosmic ray dose with thickness of material was neglected in this study due to the extreme penetrating power of the particles. This will result in a slight uncertainty for the dose estimates in the thick walled cylinders. In converting the values of absorbed dose (rad) to the "dose equivalent (rem)" values given in the previous table, a Quality Factor (QF) of 1.0 was used (see Supplemental Information - Section I). There is some controversy as to what biological significance should be associated with the high-energy, heavy-nuclear constituent of the cosmic radiation and what effect it may have on man exposed to such radiation during extended stays in space (Ref. 2). This is a question which may have to be decided by experiments conducted during the space station and space base missions.

Nuclear Reactors

The crew will be exposed to neutron and gamma radiations from reactors used in the proposed power generators. The amount of exposure will be greatly dependent on the thickness and type of reactor shielding and the distance between the reactor and the crew. Since these factors have not been defined, it is difficult to obtain accurate estimates of the dose rates in the crew areas. A dose rate of 0.048 rem per day, estimated from preliminary reactor design studies, is assumed in this study. The variation of the reactor-produced radiation with the thickness of material has been neglected, since neutrons and gamma rays are most difficult to stop with relatively small amounts of shielding. The Quality Factors recommended for use in determining the equivalent dose due to reactor produced neutrons are those given in Reference 2.

If only a partial or shadow shield is used for the reactor shielding, extremely high dose rates ($\sim$ 100 rem/hour) may be encountered during rendezvous or other activities which take the crew into the region unprotected by the shadow shield. Such a situation might require special shielding and dosimetry on manned shuttle crafts, rapid rendezvous, docking ports located in the shielded region, etc.

Trapped Radiation

The earth's magnetic field provides the mechanism which traps charged particles in belts about the Earth. Electrons and protons are trapped in a region about the equator extending in geomagnetic latitude to about $\pm 50^{\circ}$ and in altitude from the top of the atmosphere to the outer limits of the magnetosphere. Figures 2 and 3 show the spatial distribution of electrons and protons respectively.

The near-earth trapped radiation belts are approximately azimuthally symmetric, with an exception being the South Atlantic anomaly. The earth's magnetic field can be approximated by a magnetic dipole whose axis is displaced 450 kilometers from the center of the earth and tilted 10° with respect to the spin axis of the earth. In addition, the magnetic field is anomalously low in the region over the South Atlantic allowing the radiation belts to reach their lowest altitude (Figure 4). Figure 5 reflects the presence of the anomaly in the area where proton fluxes are encountered at an altitude of 160 nautical miles. The natural occurring trapped radiation environment in the anomaly region remains fairly constant with time although it does fluctuate with solar activity. In addition to the electrons in the anomaly region at low altitudes, electrons will also be encountered in the auroral zones.

The trapped radiation to be encountered in a 200 nautical mile polar orbit and in a 270 nautical mile, 55° inclination orbit has been determined. The electron and proton energy spectra are shown in Figures 6 and 7 respectively. The radiation dose produced by these environments at the center of a cylinder was determined. Cylinder wall thicknesses of

1.0 to 15 gm/cm^2 and three dose points: point tissue (no phantom), phantom skin (tissue depth - .07 mm), and phantom depth (tissue depth - 5 cm), were considered. The resulting proton and electron-point, skin, and depth dose versus cylinder wall thickness are shown in Figure 8 for the 270 nautical mile orbit and in Figure 9 for the 200 nautical mile orbit. A discussion of the calculations for the trapped radiation environment is given in Supplemental Information, Section II.

The trapped radiation environment to be encountered at synchronous orbit altitudes is also composed of protons and electrons. The trapped protons, having a mean energy of 100 kev, interact only with the material which is within a few microns of the surface of the spacecraft. The proton environment, being of no direct biological significance, will not be discussed further; however, a detailed description of the environment can be found in Reference 3. The electron environment at synchronous altitude is characterized by variations in particle intensity of several orders of magnitude over periods as short as a few hours. However, for extended synchronous altitude missions, a local time averaged environment can be used. The local time averaged electron energy spectrum for an equatorial synchronous orbit is shown in Figure 10. The environment encountered by synchronous orbit missions having different inclinations will encounter less than the equatorial environment (Ref. 4). The electron-point, skin, and depth dose versus cylinder wall thickness are shown in Figure 11 for one day in a equatorial earth-synchronous orbit.

SECTION II: "UNEXPECTED" RADIATION ENVIRONMENT

A contingency or "unexpected" radiation environment could result from a solar particle event or a high altitude nuclear event. Since these contingencies can be quite severe, the environments and the hazard they may present to the space station and space base missions should be considered.

High Altitude Nuclear Events

A rather dramatic increase in the electron environment in the South Atlantic anomaly occurred in July 1962 when the Starfish high altitude nuclear detonation injected copious numbers of electrons into the trapping magnetic field (Ref. 5). Most of the lower energy electrons have decayed away, although some high energy electrons still remain.

The Starfish event produced an environment which would not have permitted extended manned missions at low earth orbits for some months after the event. Since the Starfish event is by far not the largest event possible, it must be assumed that the near-earth trapped radiation environment could be enhanced to the extent that the entire crew of an earth-orbiting space station would have to be returned to earth as soon as possible.

Solar Particle Events

Solar particle events are the emission of charged particles from disturbed regions on the sun called solar flares. Solar particle events are composed of energetic protons and alpha particles; they occur sporadically and last as long as several days. The solar particle event environment is virtually unpredictable, making it impossible to determine the environment to be encountered by missions 5 to 15 years in the future. However, the solar particle event environment which should be used in the design of spacecrafts to be used for extended manned flights in the period 1975 - 1985 is given in the following:

Protons

$$N_p(>T) = \begin{cases} 1.45 \times 10^{12}\, T^{-1.2}; & 1\text{ MeV} \leq T \leq 10\text{ MeV} \\ 7.08 \times 10^{11}\, e^{-P(T)/67}; & 10\text{ MeV} \leq T \leq 30\text{ MeV} \\ 2.18 \times 10^{11}\, e^{-P(T)/100}; & T \geq 30\text{ MeV} \end{cases}$$

Alphas

$$N_\alpha(>T) = \begin{cases} 5.65 \times 10^{10}\, e^{-P(T)/59}; & 10\text{ MeV} \leq T \leq 30\text{ MeV} \\ 3.49 \times 10^{10}\, e^{-P(T)/67}; & T \geq 30\text{ MeV} \end{cases}$$

where N_p (>T) and N_α (>T) are the integral fluxes in units of protons/cm^2 and alphas/cm^2, respectively. T is the particle's kinetic energy in units MeV and P(T) is the particle's magnetic rigidity in units MV given by

$$P(T) = \frac{1}{Ze} \sqrt{T (T + 2 m_o C^2)}$$

where the quantity Ze is the magnitude of the particle's charge in units of electron charge, i.e. Ze = 1 for protons and Ze = 2 alphas. The rest mass energy for the particle is given by $m_o C^2$, i.e. $m_o C^2 = 938$ MeV for protons and 3728 MeV for alpha particles.

The environment given above is based on an integration of all particle events observed over approximately six years of the 19th solar cycle. The energy distributions were based on data from Webber (Ref. 6) and Foelsche (Ref. 7). Somewhat higher integral fluxes for N(>30 MeV) were reported by Masley (Ref. 8) for some of the 19th solar cycle events. These data were used for the integral flux, N(>30 MeV). The integration of all particle events to date in the 20th solar cycle gives a value approximately 20 times less than for the 19th cycle. This is probably due to the fact that the overall solar activity in the 20th cycle is less than the 19th cycle as measured by sunspot number. However, a clear dependence of number and size of particle events on sunspot number has not been demonstrated. The 19th solar cycle was the largest, in terms of sunspot number, observed to date. Assuming that the number of particles emitted as a result of solar activity is generally dependent on the size of the sunspot cycle, manned missions in the period 1975-1985 should not expect to encounter a more severe solar particle event environment than that given above.

The solar particle event environment given above was used along with the appropriate proton and alpha Quality Factors (see Supplemental Information - Section I) in calculating the resultant radiation exposure. The point, skin, and depth dose versus cylinder wall thickness for the design solar particle event environment are shown in Figure 12.

SECTION III: RESULTS

An estimate of the total "expected" radiation exposure per day was obtained by summing the trapped radiation, cosmic ray, and reactor dose rate estimates. Figure 13 shows the total daily dose versus the wall thickness of an aluminum cylinder for the various dose points for the 200 and 270 nautical mile orbits and Figure 14 for the synchronous altitude orbit.

The preliminary skin and depth dose limits to be used in the planning of the space station and space base missions are a depth dose of 25 rem and a skin dose of 250 rem. These limits and the estimates of the "expected" doses would allow for planned crew stay times in a vehicle with a wall thickness equivalent to 1.0 gm/cm^2 of aluminum, of 185 days for the 270 nautical mile orbit, 347 days for the 200 nautical mile orbit, and 140 days for the synchronous altitude orbit. The estimates of the "expected" radiation levels may be somewhat conservative due to the use of simplified spacecraft geometries. Later calculations using a more detailed description of the vehicle may show that much longer crew stay times can be obtained.

The unexpected or contingency environments can present a more serious problem than does the expected environment. Spacecraft designed for manned flights in the period 1975-1985 should provide, within themselves, adequate protection from solar particle events. Since it would not be feasible to make all the exterior walls of the spacecraft thick enough to provide the necessary protection, a logical approach would be to design a radiation shelter (see Supplemental Information - Section III).

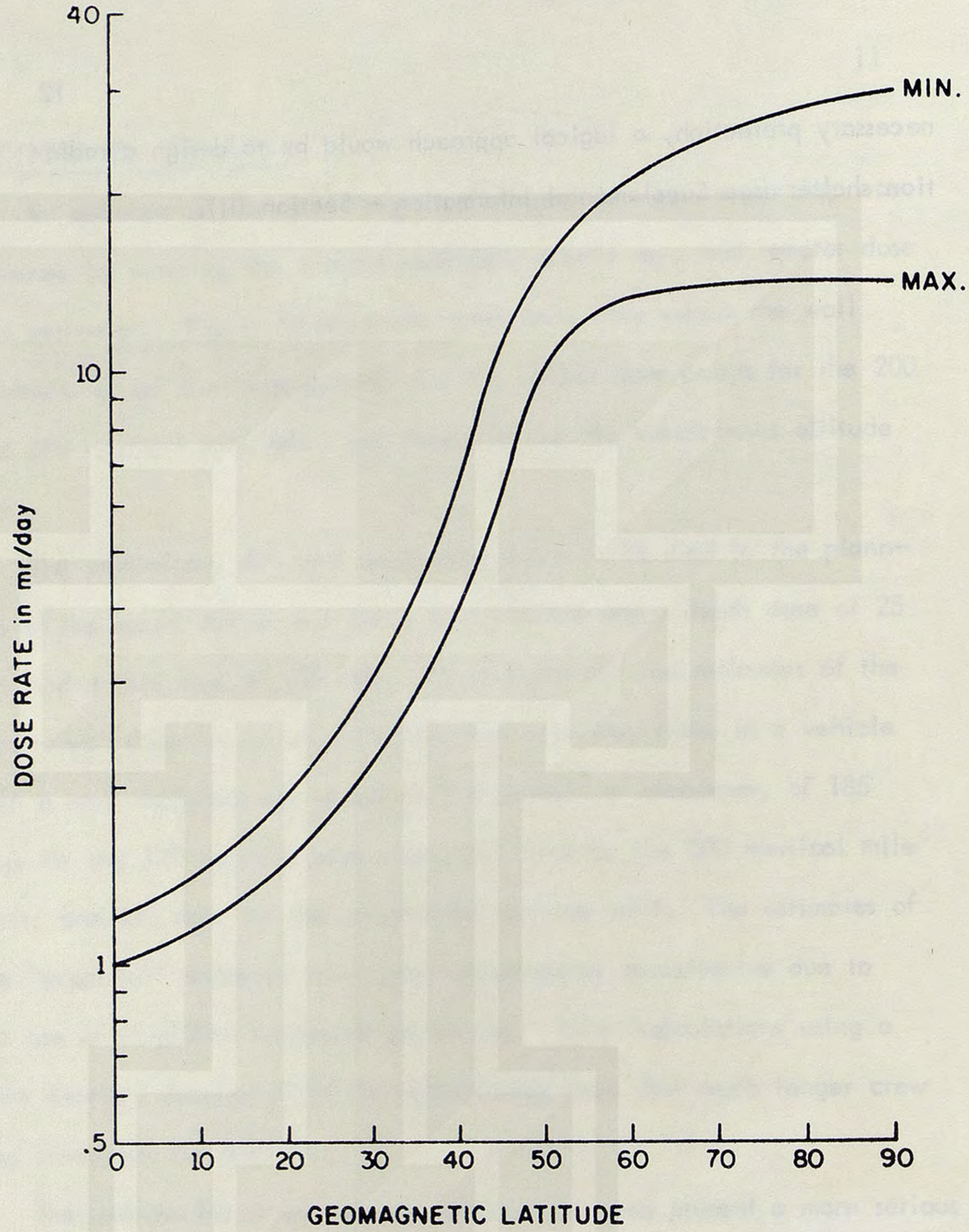


Figure 1. Cosmic-ray dose rate above the atmosphere as a function of geomagnetic latitude during solar maximum and minimum.

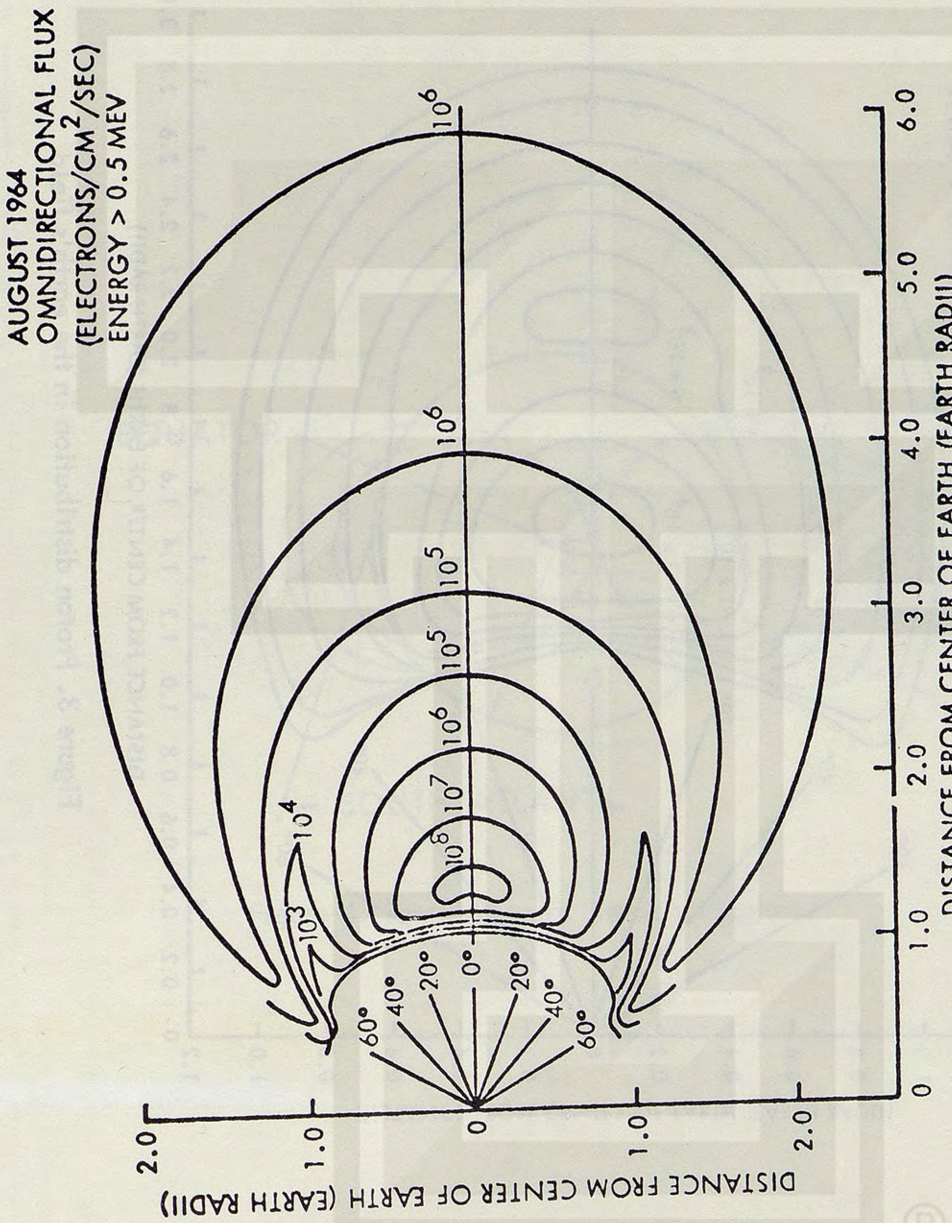


Figure 2. Electron distribution in the earth's field

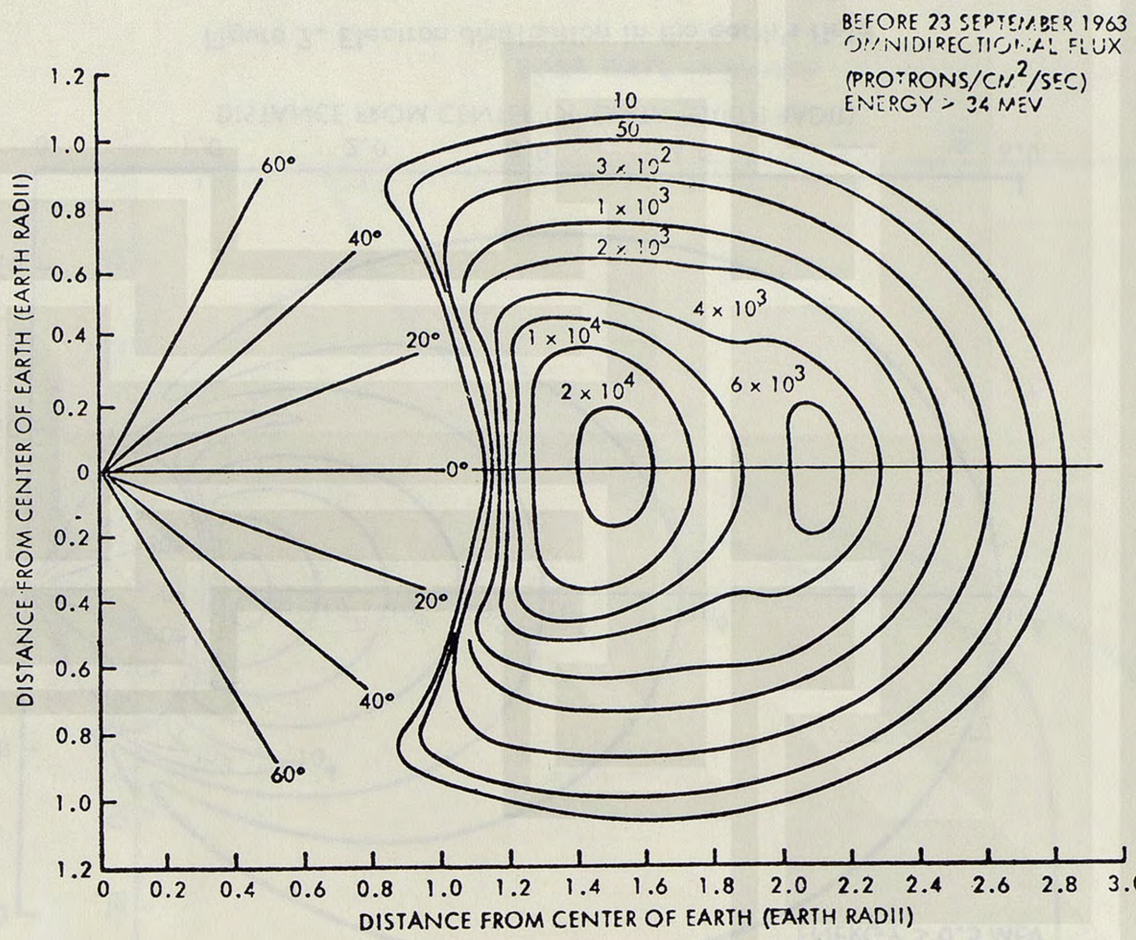


Figure 3. Proton distribution in the earth's field

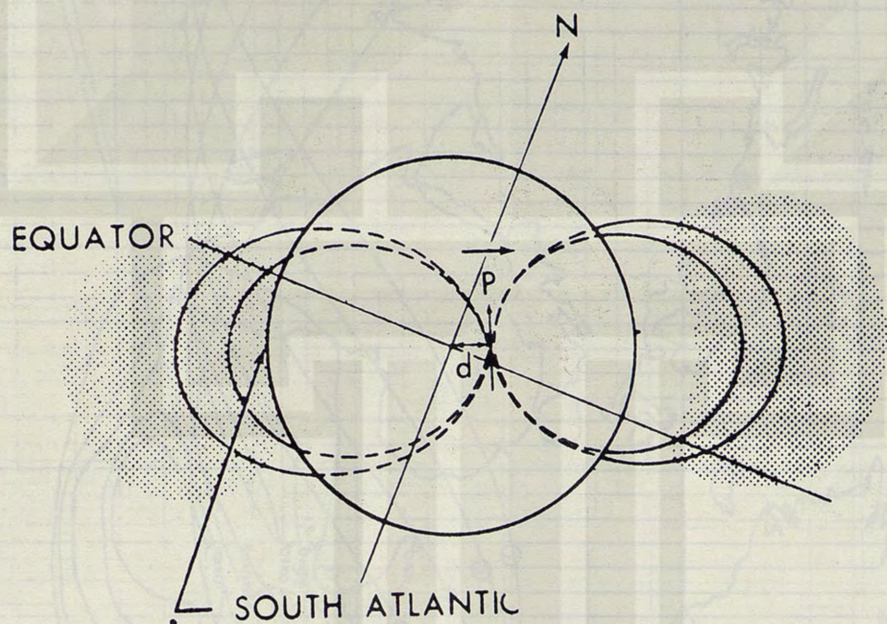


Figure 4. South Atlantic anomaly diagram

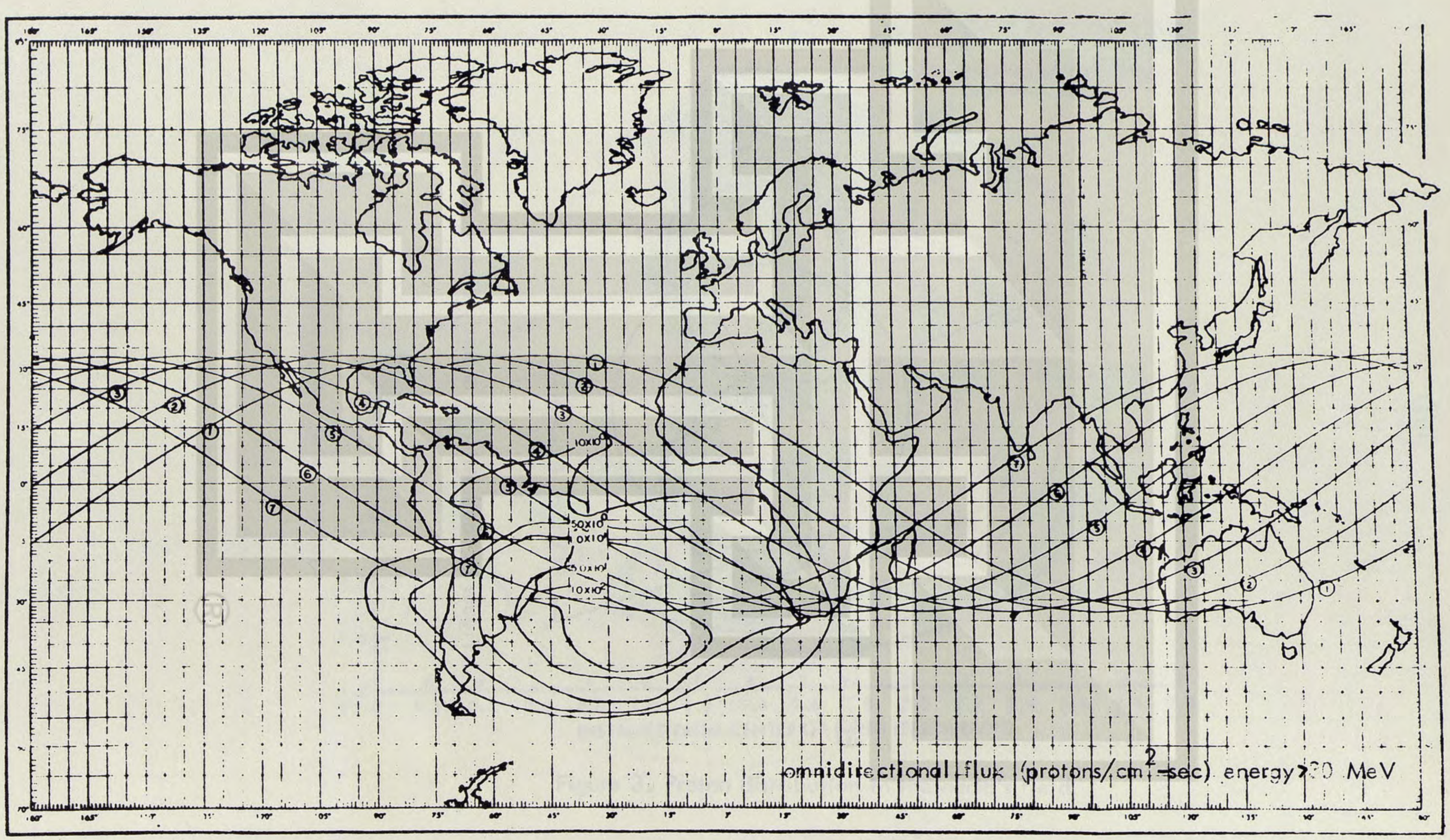


Figure 5. Proton flux densities at an altitude of 162 n.mi.

Figure 6

ELECTRON DIFFERENTIAL ENERGY SPECTRA

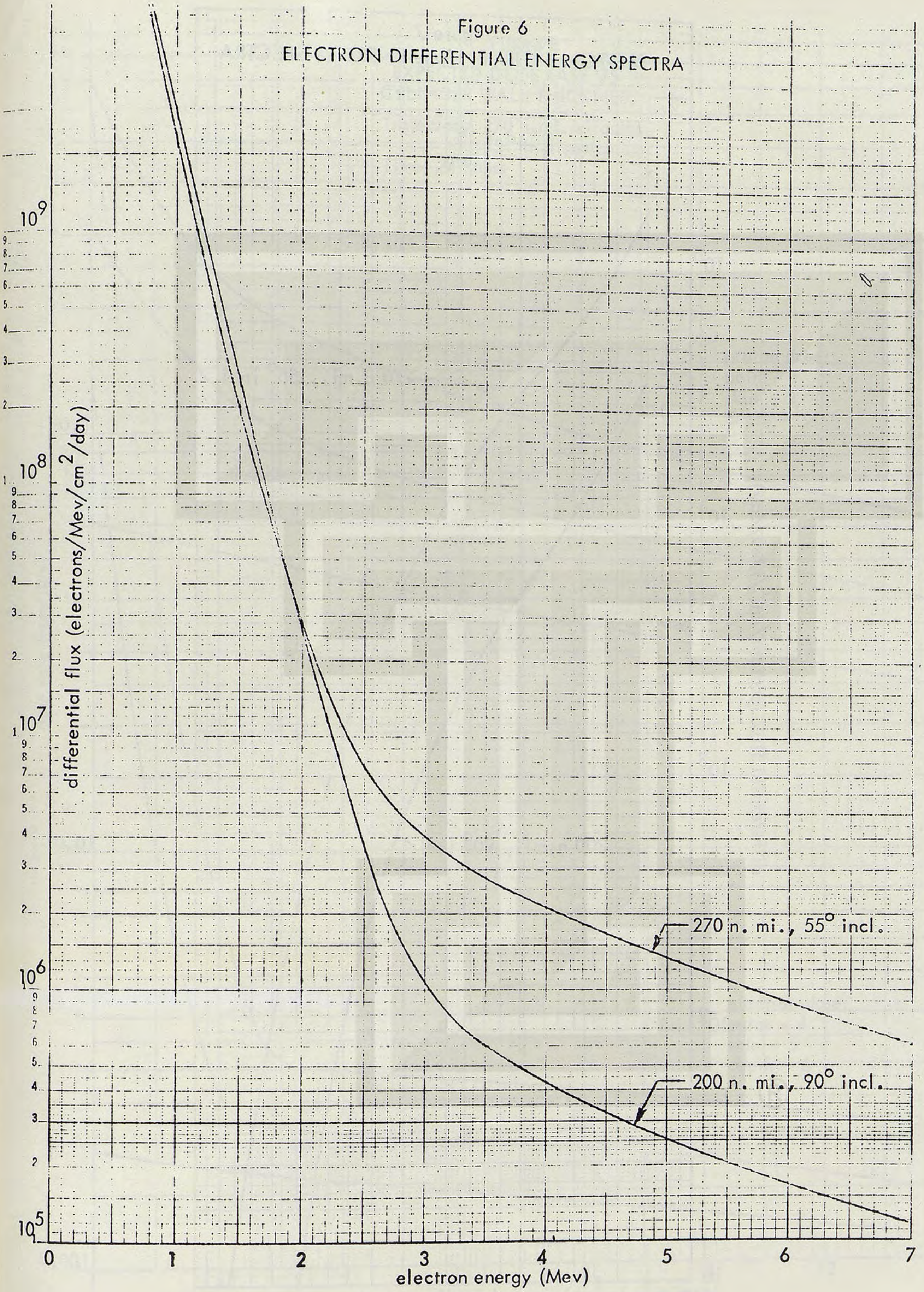
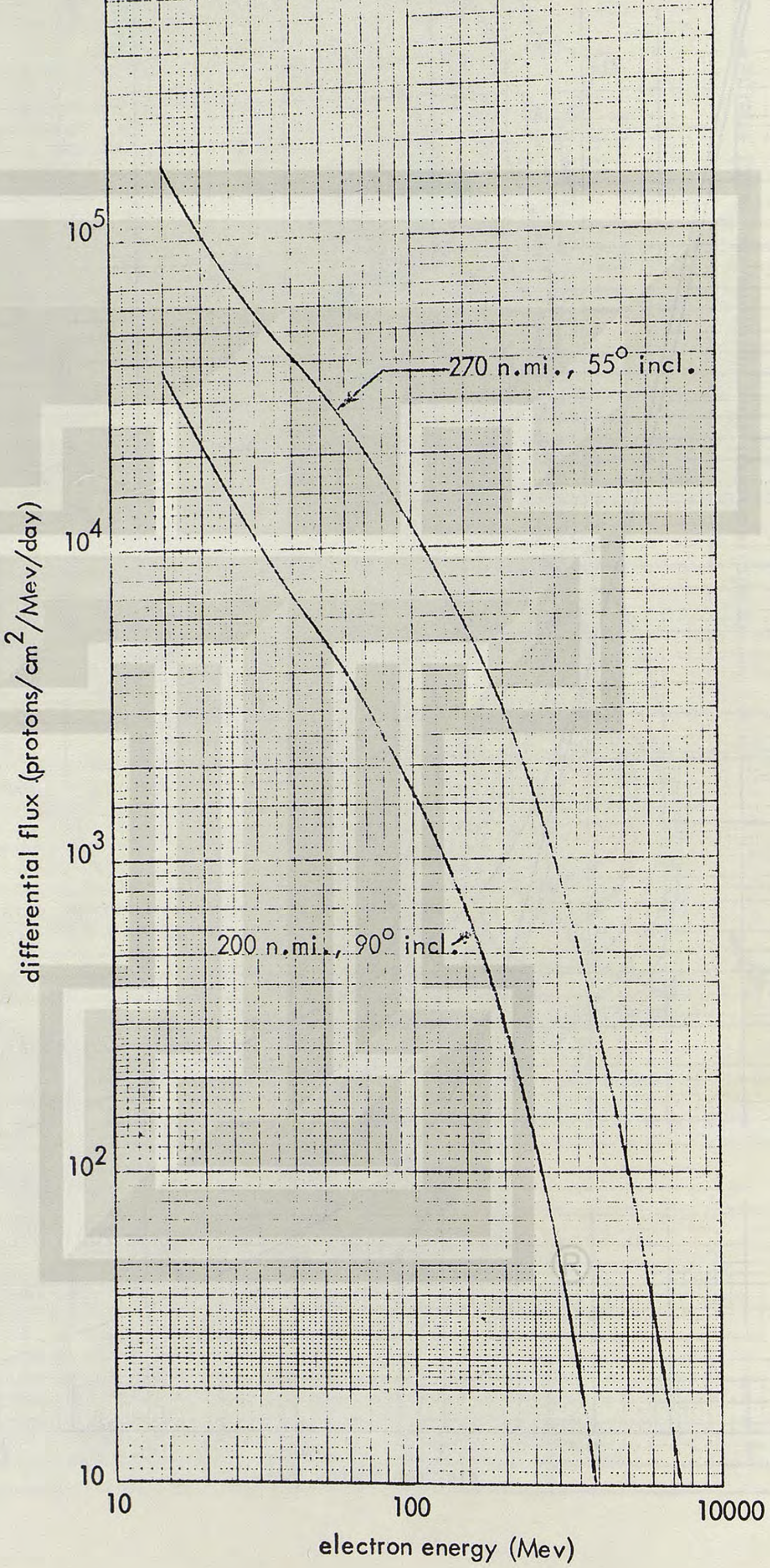


Figure 5. Proton flux densities at an altitude of 162 n.mi.

Figure 7
PROTON DIFFERENTIAL ENERGY SPECTRA



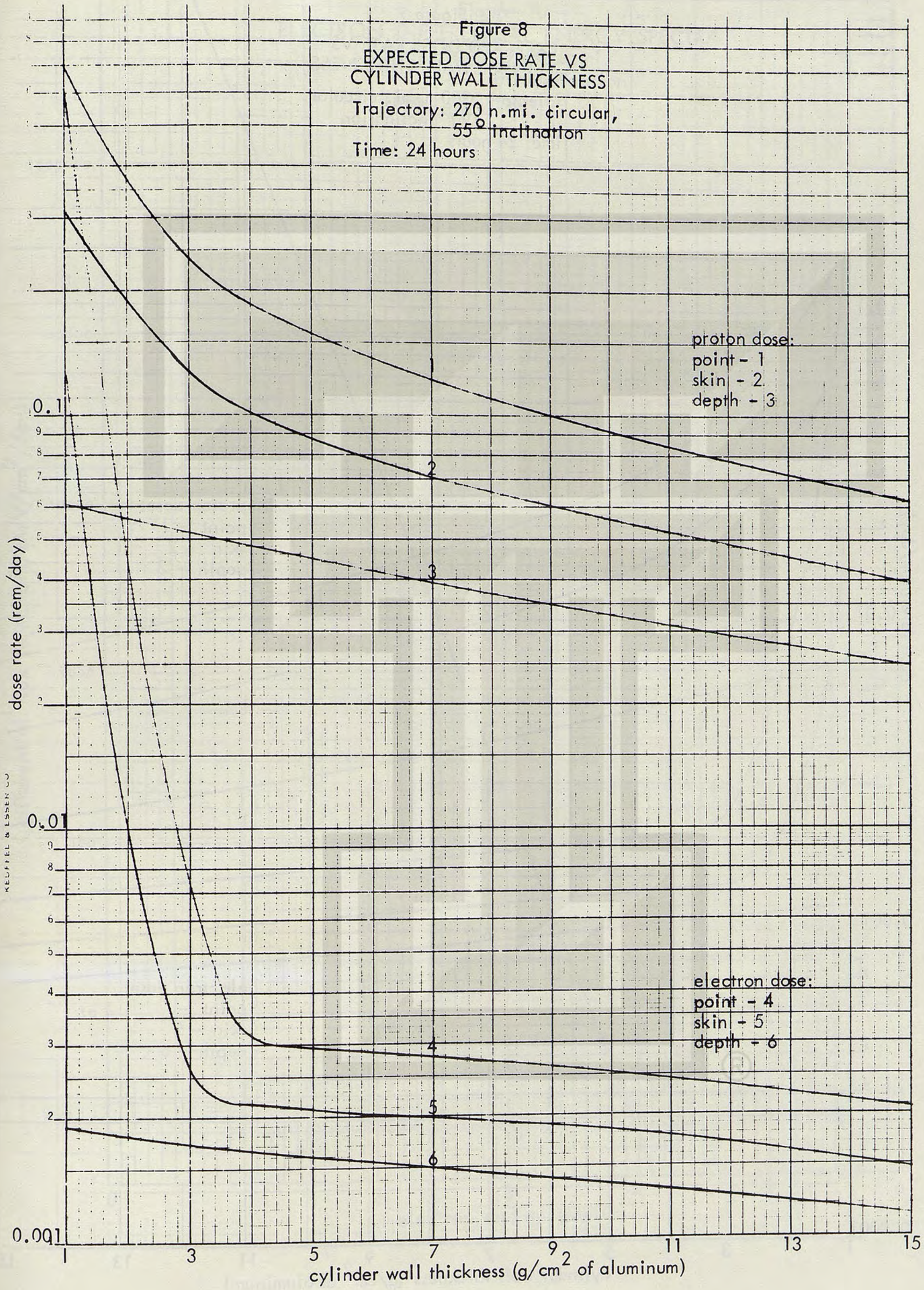


Figure 8
EXPECTED DOSE RATE VS
CYLINDER WALL THICKNESS
Trajectory: 270 n.mi. circular,
55° inclination
Time: 24 hours
proton dose:
point - 1
skin - 2
depth - 3
electron dose:
point - 4
skin - 5
depth - 6
dose rate (rem/day)
0.1
0.01
0.001
cylinder wall thickness (g/cm2 of aluminum)
1
3
5
7
9
11
13
15

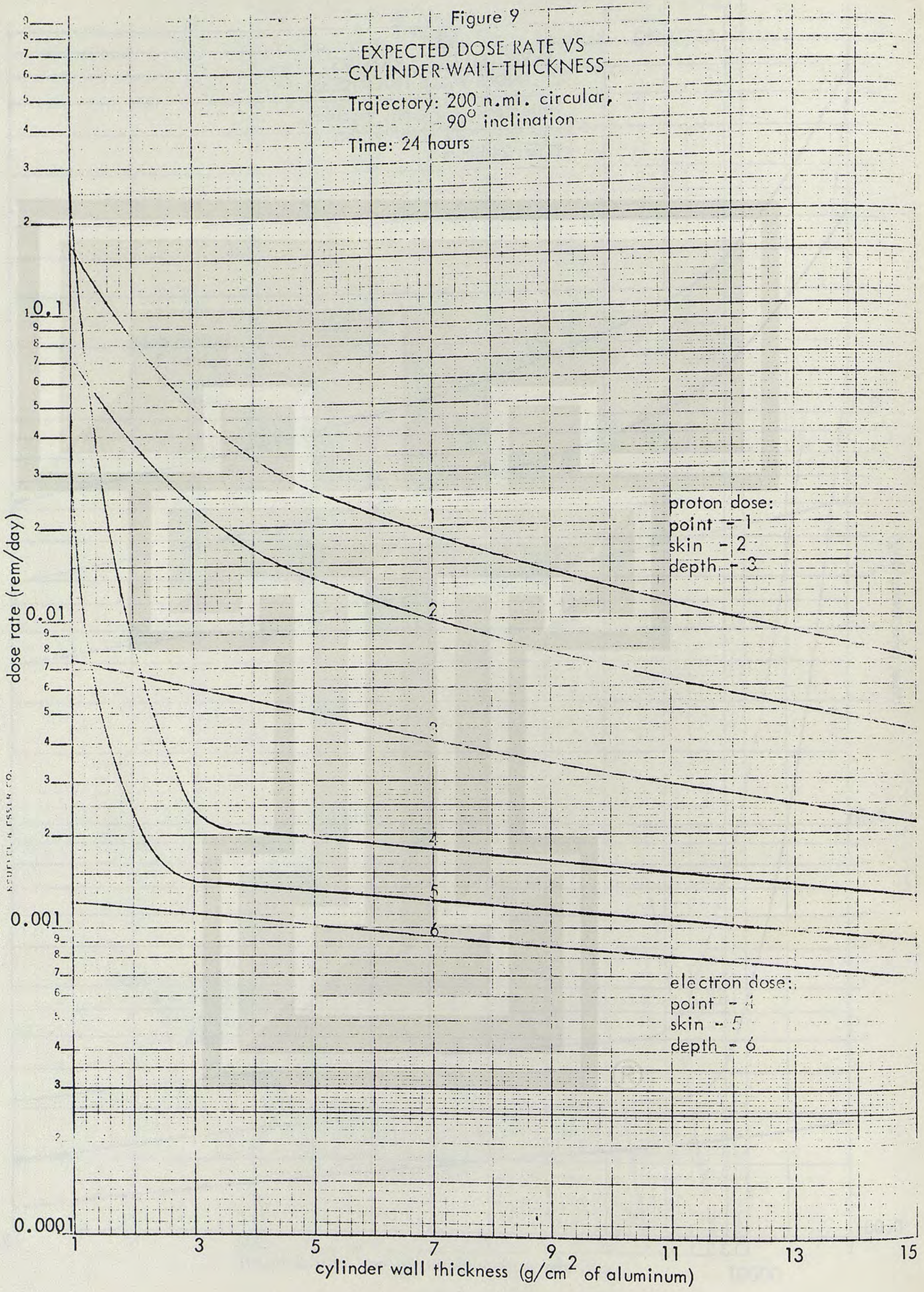


Figure 9
EXPECTED DOSE RATE VS
CYLINDER WALL THICKNESS
Trajectory: 200 n.mi. circular,
90° inclination
Time: 24 hours
proton dose:
point - 1
skin - 2
depth - 3
electron dose:
point - 4
skin - 5
depth - 6
dose rate (rem/day)
0.1
0.01
0.001
0.0001
1
3
5
7
9
11
13
15
cylinder wall thickness (g/cm2 of aluminum)

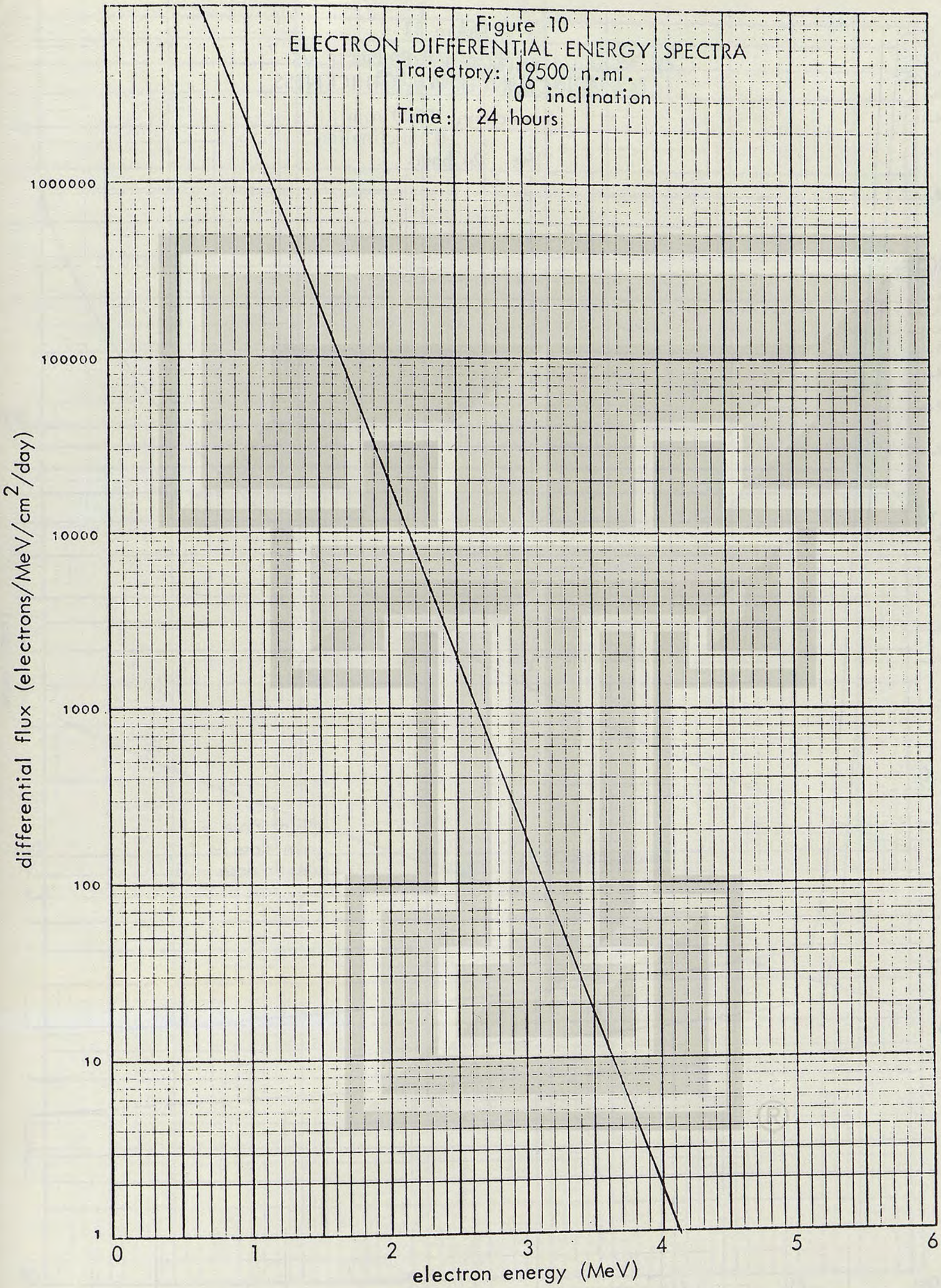


Figure 10
ELECTRON DIFFERENTIAL ENERGY SPECTRA
Trajectory: 19500 n.mi.
0° inclination
Time: 24 hours
1000000
100000
10000
1000
100
10
1
differential flux (electrons/MeV/cm2/day)
0
1
2
3
4
5
6
electron energy (MeV)

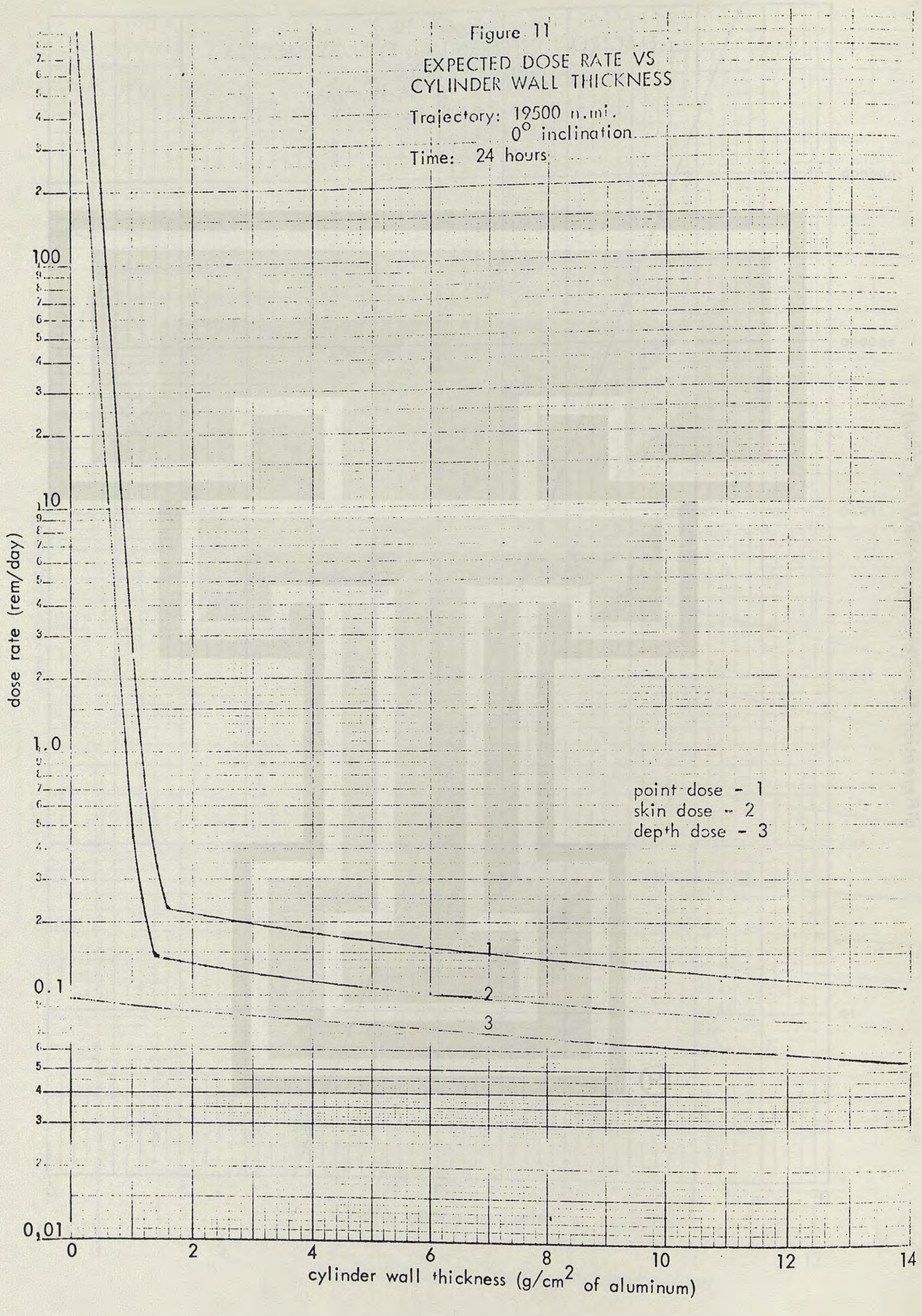


Figure 11
EXPECTED DOSE RATE VS
CYLINDER WALL THICKNESS
Trajectory: 19500 n.mi.
0° inclination
Time: 24 hours
point dose - 1
skin dose - 2
depth dose - 3
1
2
3
100
10
1.0
0.1
0.01
0
2
4
6
8
10
12
14
dose rate (rem/day)
cylinder wall thickness (g/cm2 of aluminum)

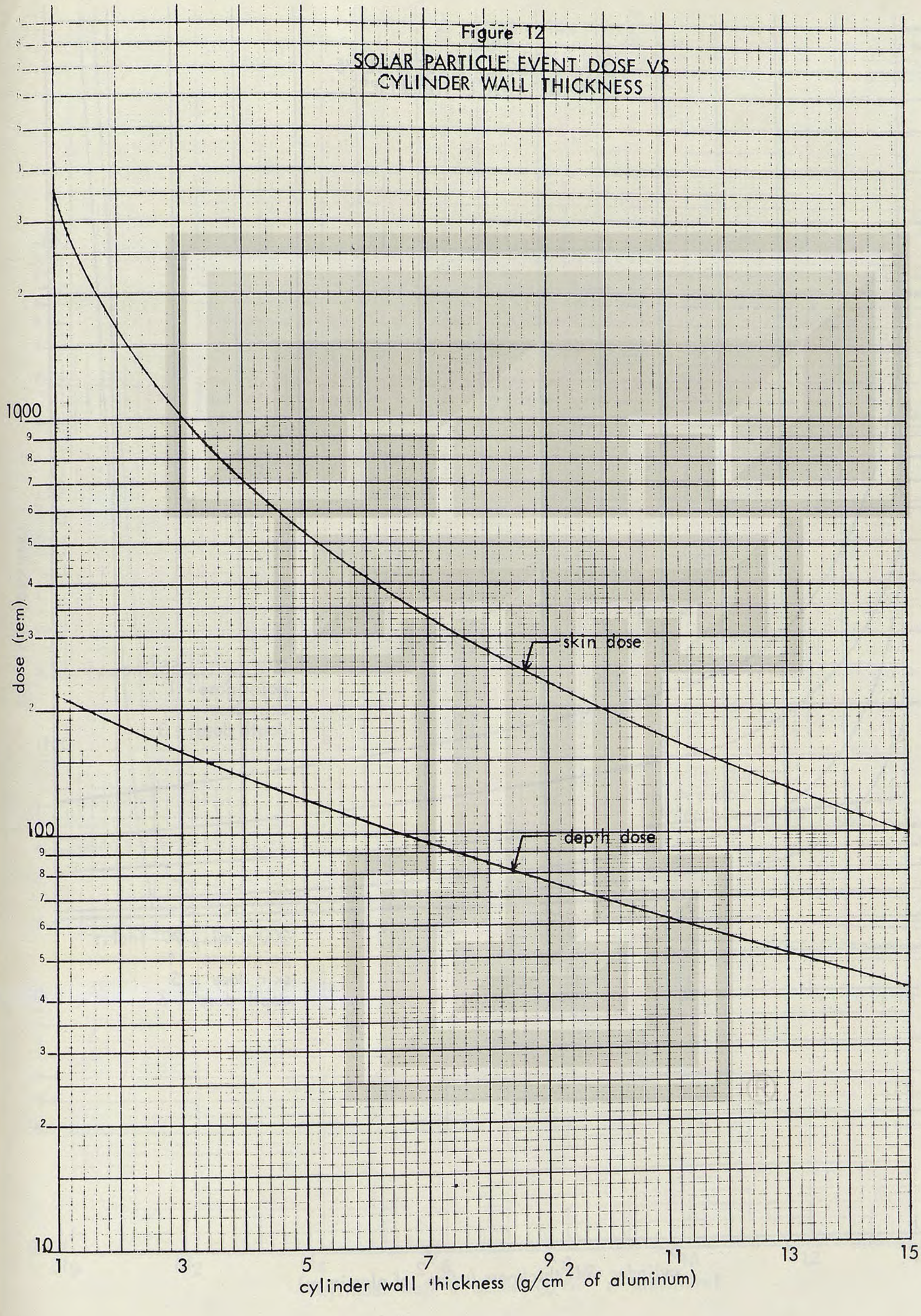


Figure T2
SOLAR PARTICLE EVENT DOSE VS
CYLINDER WALL THICKNESS
skin dose
depth dose
dose (rem)
1000
100
10
1
3
5
7
9
11
13
15
cylinder wall thickness (g/cm2 of aluminum)

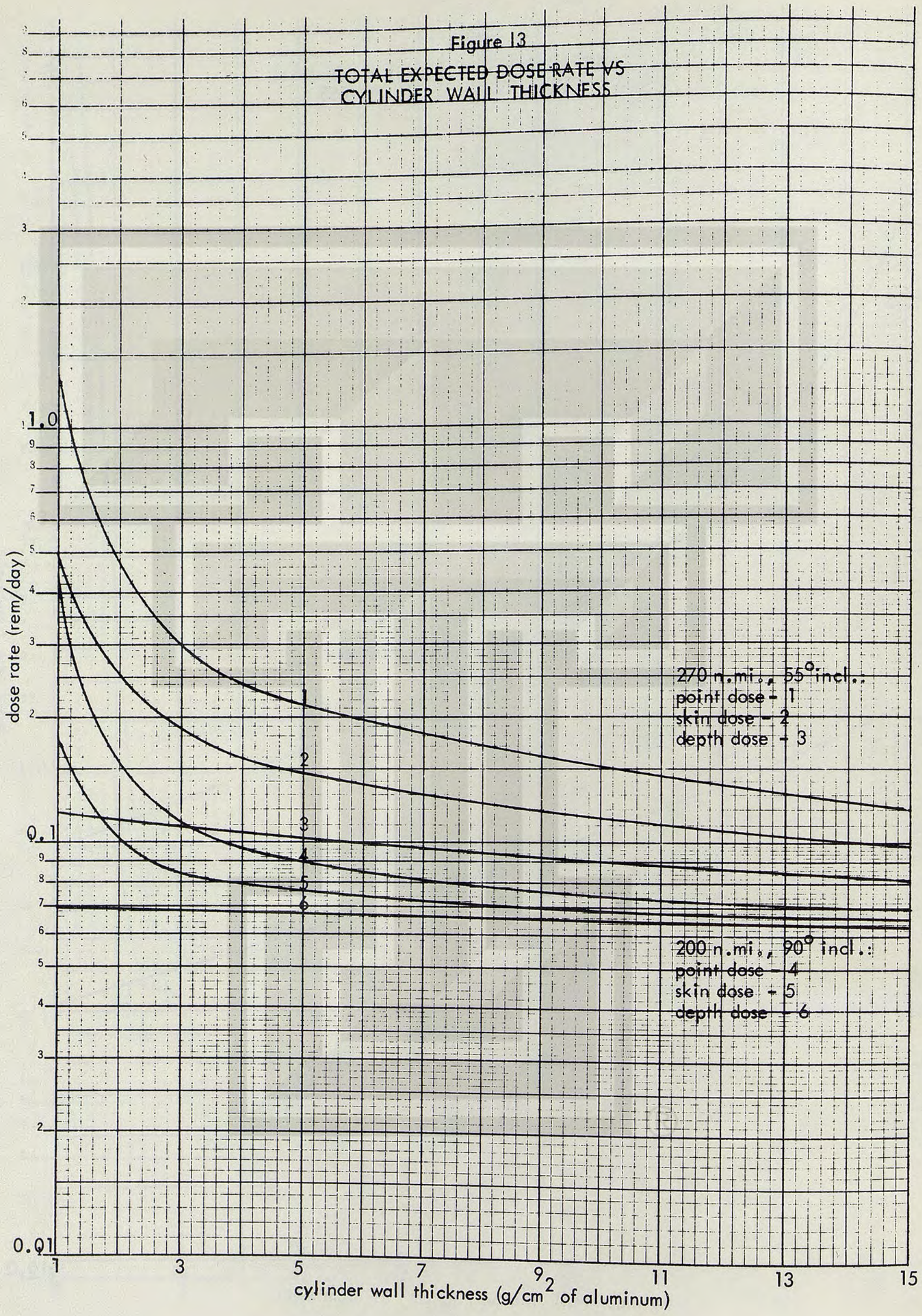


Figure 13
TOTAL EXPECTED DOSE RATE VS CYLINDER WALL THICKNESS

Figure 14

TOTAL EXPECTED DOSE RATE VS CYLINDER WALL THICKNESS

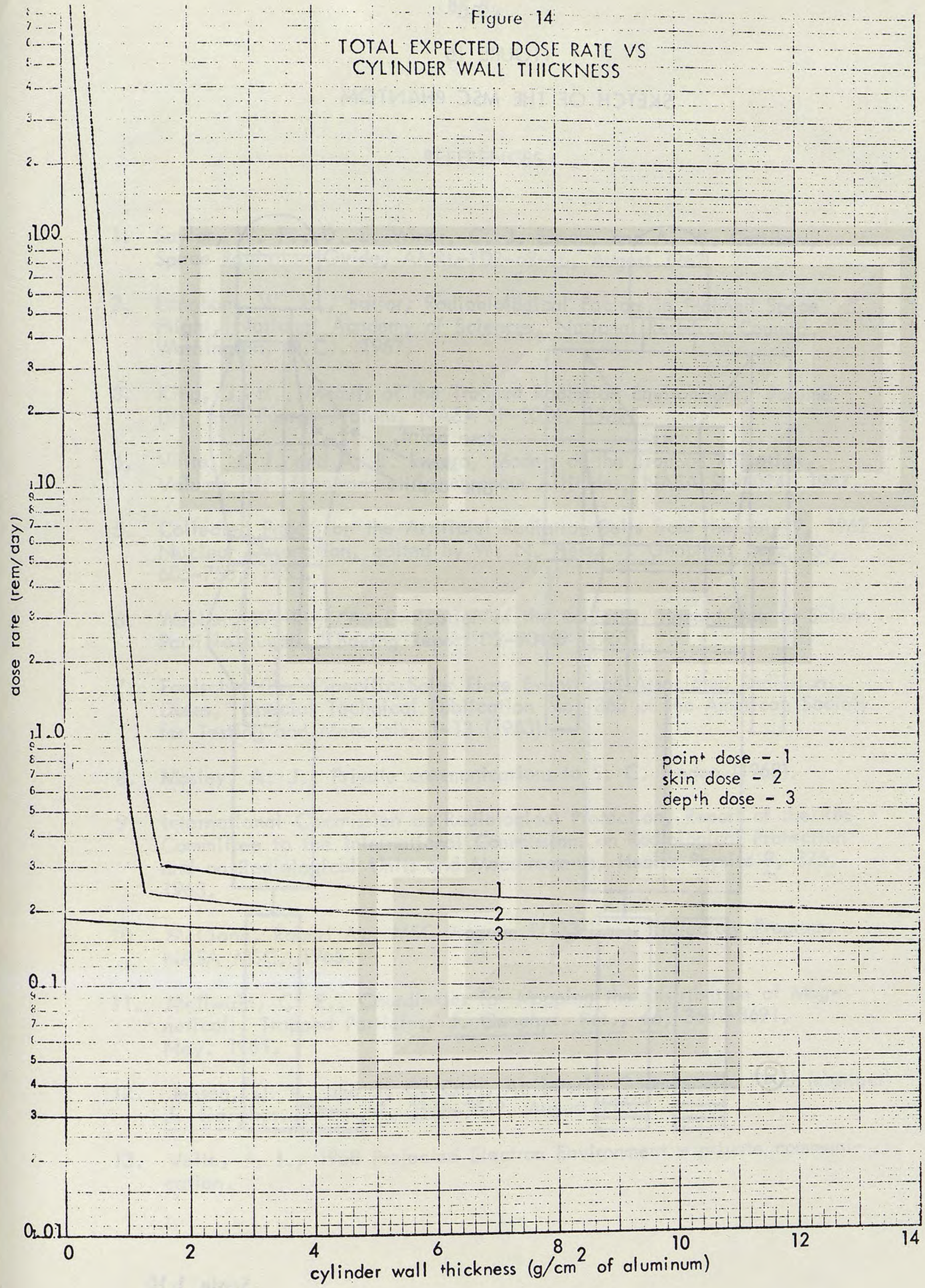
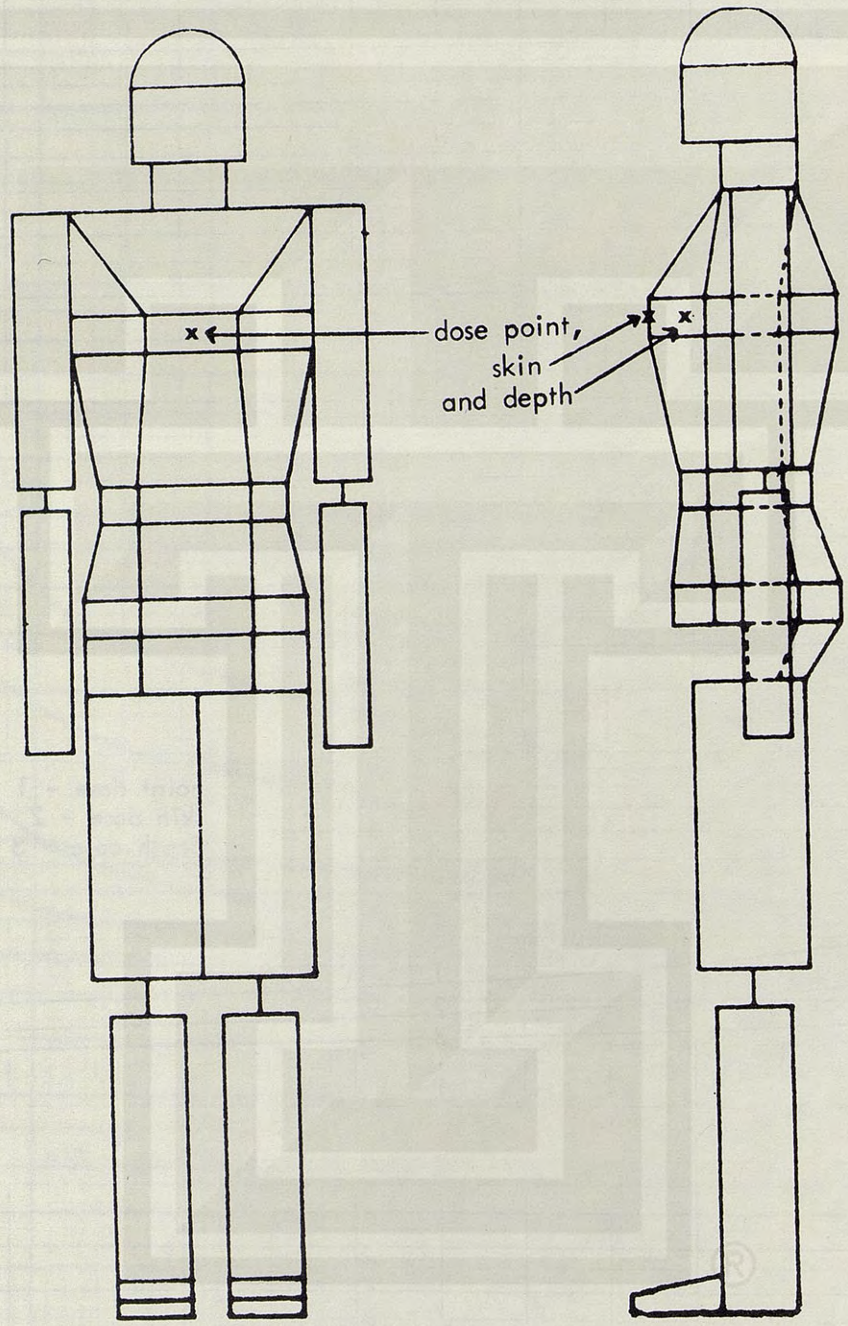


FIGURE 15

SKETCH OF THE MSC PHANTOM



Scale 1:10

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SUPPLEMENTAL INFORMATION - SECTION I

The absorbed dose of any ionizing radiation is the energy imparted through ionization per unit mass of irradiated material. The unit of absorbed dose is the rad, which is equal to an energy deposition of 100 ergs/g. Radiations of different type and quality (mass, charge, energy) produce different spatial distributions of energy deposition in tissue and thereby produce different biological responses per unit of absorbed dose. The concept of "dose equivalent" (DE) is used to take into account the difference in effect of radiations having different quality. The "dose equivalent" (in rems) is obtained from the product of the absorbed dose (in rads) and the appropriate Quality Factor (QF) and other modifying factors. $QF = 0.8 + 0.162L$, where L is the mean LET in KeV of ionization energy per micron of material (Ref. 9). The other modifying factors for this application equal 1.0. A more complete description of this concept can be found in Reference 2.

SUPPLEMENTAL INFORMATION - SECTION II

The radiation dose contributed by electrons and protons trapped in the earth's magnetic field is determined for a given shielding configuration and trajectory by the MSC Orbital Dose Code which utilizes MSC, Radiation and Fields Branch dose-calculational programs. The trajectory data were obtained using a computer program (Ref. 10) from which spacecraft positions were determined at 15 second intervals, an adequate sample rate for determining the encountered environment. The geomagnetic coordinates (B, L) which correspond to each spacecraft position were obtained from the McIlwain field-fit code (Ref. 11) and Jensen and Cain coefficients (Ref. 12). The electron energy spectra were obtained from the Vette 1968 projected electron environment (Ref. 13). The proton energy spectra were determined from the Air Force Weapons Laboratory proton flux data (Ref. 24) by fitting the flux data to a power spectrum for proton energies less than 30 MeV and an exponential spectrum for proton energies greater than 30 MeV. At the present time, the Air Force Weapons Laboratory data for proton energies greater than 40 MeV is more accurate than the data given by Vette; however, the Vette data will soon be undated to incorporate these data. The spacecraft and phantom shielding were determined with a North American Aviation shielding code (Ref. 15). A sketch of the phantom used in the calculations is shown in Figure 15. The skin and depth dose points were placed at depths of .07 mm and 5 cm of tissue, respectively, at the locations indicated. The phantom was placed at the center of an aluminum cylinder, and oriented as if it was standing on a floor parallel to the end of the cylinder. The location of the phantom is the position of highest exposure. The dimensions of the cylinder were 30 feet in height and 33 feet in diameter. One hundred g/cm^2 were used as the thickness of the ends to make allowance for other modules connected to the cylinder. Thicknesses of 1 to 15 g/cm^2 of aluminum were used for the walls (1 g/cm^2 of aluminum = 2.048 lb/ft^2 = 0.15 inch of aluminum). MSC dose calculational techniques (Refs. 16, 17, and 18) were used to attenuate the proton and electron energy spectra through the spacecraft and phantom shielding to the desired dose point. The energy deposited by the attenuated environment was then determined. The doses deposited by primary protons, primary electrons and bremsstrahlung were determined in units of rem. A QF of 1.0 was used in the calculation of electron and bremsstrahlung dose. The QF for protons used in the calculations varied from 1.0 to 20 (Supplemental Information - Section I) depending on the energy of the proton at the dose point. Because of the possible uncertainty in the model radiation environment and calculational techniques, a two sigma deviation of a factor of 2 is anticipated in the numbers presented.

SUPPLEMENTAL INFORMATION - SECTION III

The realization that (1) the environment encountered by future missions can be more severe than the expected environment; (2) that any radiation exposure can be detrimental and therefore should be kept to a minimum; (3) that operational procedures for modifying or aborting a mission may not be practical; and (4) that space station of space base vehicles designed for low-altitude, earth-orbital missions may be used in future synchronous eurrh-orbit or interplanetary mission establishes the need for a radiation shelter. The basic concept of a radiation shelter is to provide a compartment, heavily shielded in all directions, in which the crew could be housed during radiation contingency periods. The shielding for the shelter should be obtained by expeditious placement of existing systems, equipment, storage tanks, etc., about the walls of the shelter. A possible location for the shelter would be an area which housed the crew sleeping, eating, waste management, and recreational facilities. This location would allow the crew to remain in a compartment which was self-supporting. This would be particularly desirable if the contingency situation persisted for a long period of time. The location would have the added advantage of reducing the amount of radiation exposure resulting from the trapped and galactic cosmic radiation, nuclear power sources, etc., since the crew as a matter of course would spend a significant amount of the mission time in these quarters and therefore in the shelter.

There are many advantages to having a radiation shelter aboard a space station. If a radiation contingency such as a solar particle event were to occur, the crew could seek refuge in the shelter, affording the crew the maximum possible protection. A radiation shelter, designed to utilize existing materials and equipment, would provide the greatest protection for a minimum of additional weight. This approach to radiation protection places little or no radiation constraints on the wall thickness of other parts of the station. The shelter would be a compartment which, due to the structural integrity of its walls, would provide the greatest protection against micrometeoroid puncture of accidental collision. It would also provide an ideal location for a photographic film repository.

Although a radiation shelter would be very beneficial in reducing the potential hazard of the solar particle event and reducing the amount of the "expected" crew exposure, it still might not afford adequate crew protection for extended periods if a nuclear event significantly enhanced the near-earth radiation belts. Such a situation would require the crew to return to earth in order to avoid a lethal exposure.