NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

NASA SP-8054

# SPACE RADIATION PROTECTION

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

# FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all previously issued monographs in this series can be found at the end of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniform design requirements for NASA space vehicles.

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# CONTENTS


1. INTRODUCTION . . . . . 1

2. STATE OF THE ART . . . . . 3

2.1 Space Radiation Environment . . . . . 6
2.1.1 Solar Cosmic Rays . . . . . 6
2.1.2 Trapped Radiation . . . . . 7
2.1.3 Galactic Cosmic Rays . . . . . 8
2.2 Allowable Radiation Doses . . . . . 9
2.3 Dose Analysis . . . . . 9
2.3.1 Proton Dose Analysis . . . . . .10
2.3.2 Heavy-Nuclei Dose Analysis . . . . . .12
2.3.3 Electron and Bremsstrahlung Dose Analysis . . . . . .13
2.4 Shielding Design . . . . . .14
2.5 Testing . . . . . .15
2.5.1 Measurement of Radiation Transmission . . . . . .16
2.5.2 Measurement of Mass Distribution . . . . . .16
2.5.3 Unmanned Experiments . . . . . .16
2.5.4 Instrumented Flight Tests . . . . . .17

3. CRITERIA . . . . . .17

3.1 Space Radiation Environment . . . . . .17
3.2 Allowable Radiation Doses . . . . . .17
3.3 Dose Analysis . . . . . .18
3.4 Shielding Design . . . . . .18
3.5 Testing . . . . . .18

4. RECOMMENDED PRACTICES . . . . . .18

4.1 Space Radiation Environment . . . . . .19
4.1.1 Solar Cosmic Rays . . . . . .20
4.1.2 Trapped Radiation . . . . . .20
4.1.3 Galactic Cosmic Rays . . . . . .20

4.2 Allowable Radiation Doses . . . . . 21
4.3 Dose Analysis . . . . . 21
4.3.1 Proton Dose Analysis . . . . . 22
4.3.2 Heavy-Nuclei Dose Analysis . . . . . 28
4.3.3 Electron Dose Analysis . . . . . 28
4.3.4 Bremsstrahlung Dose Analysis . . . . . 29
4.4 Shielding Design . . . . . 32
4.5 Testing . . . . . 34

**REFERENCES** . . . . . 35

**NASA SPACE VEHICLE DESIGN CRITERIA MONOGRAPHS ISSUED TO DATE** . . . . . 45

# SPACE RADIATION PROTECTION

## 1. INTRODUCTION

Space vehicles are subjected to a variety of penetrating energetic radiations present in space that generally have adverse effects on vehicle materials, components, or occupants, and these may require some form of radiation protection. Adverse effects manifest themselves in the form of changes in properties of materials or components which impair their function, or they are physiological changes in vehicle occupants which impair their function or compromise their well-being. If insufficient radiation protection is provided, these effects can result in mission failure or permanent injury to vehicle occupants, or both.

The purpose of this monograph is to establish criteria and procedures for determining doses caused by penetrating space radiation and for the design of appropriate protection for space vehicles. The objective is to avoid exceeding specified allowable levels of radiation dose and/or dose rate for the duration of the mission. The approach is first to calculate the doses received by each radiation-sensitive item, considering the protection inherent in the vehicle structure and contents, and the space radiation environment encountered during the mission. If any doses exceed allowable limits, then the design of shielding is implemented to reduce the doses to meet the specifications, unless the adjustment of mission parameters or system design (or specifications) can eliminate the necessity.

The prevailing types and sources of penetrating space radiation are:

- Solar cosmic rays, consisting chiefly of protons, with some alpha particles (helium nuclei) ejected sporadically from the sun during some solar-flare events

- Magnetically trapped protons and electrons in the vicinity of the earth and other planets

- Galactic cosmic rays, consisting of a continuous flux of protons and comparatively fewer heavier nuclei.

Other radiations that make up the total space radiation environment are not considered in this monograph, either because their intensity is too small to constitute a significant hazard relative to the prevailing sources (e.g., solar X-rays) or because their low penetrability limits their influence to surface effects (e.g., thermal radiation, solar wind). A detailed description of the total space radiation environment is contained in other planned monographs in the NASA design criteria series.

The major parameters that determine the radiation dose are

- Type of radiation
- Flux intensity
- Flux energy spectrum
- Flux directionality
- Type and spatial distribution of materials between radiation source and component
- Material in which the dose is determined

The response of a material or component to a radiation field generally varies with the type of radiation, and is dependent on the magnitude, rate, and pattern of energy deposition. However, the response can usually be related directly to the absorbed dose, or the energy absorbed per unit mass. The most commonly used dose unit is the rad, defined as the absorption of 100 ergs/g (0.01 J/kg). Human biological response is often (but not always) expressed in rem, a special unit called "dose equivalent." Other terms are also used, but for the sake of being definite and consistent, the term dose will be used throughout this monograph. These and other radiation quantities and units are defined in references 1 and 2.

Radiation protection is potentially important for missions at altitudes above about 200 km from the earth. The earth's atmosphere at these altitudes offers little protection by way of radiation absorption and trapped radiation attrition. The trapped radiation environment is a hazard for near-earth missions, and the solar cosmic-ray and galactic cosmic-ray environments are hazards for missions outside the protection of the earth's magnetic field (e.g., for lunar and interplanetary missions, and for near-polar or high-altitude orbital missions).

In manned space vehicles, the most critical dose constraint is usually the allowable biological dose; although some photographic film is more sensitive to radiation, it is

easier to protect. In unmanned systems, electrical circuits, solid-state electronic components, solar cells, and other radiation-sensitive materials usually impose the most stringent requirements for radiation protection. If the dose is excessive, it can be reduced to an acceptable level by interposing shielding material between the radiation source and the component. The effects of nuclear and space radiation on structural materials are treated in a separate monograph on that subject (NASA SP-8053).

Radiation sources other than space radiation (e.g., those associated with onboard nuclear propulsion and power systems) are not treated in this monograph, but they must be accounted for in the specification of allowable doses from space radiation.

## 2. STATE OF THE ART

Increased knowledge of radiation-material interactions and the space-radiation environment and the development of high-speed computers for performing complex analyses have resulted in rapid advances in the analysis of radiation protection in recent years. However, actual hardware experience involving the design, testing, and application of space radiation shielding for complex situations, such as manned spacecraft, has been limited. The approach has generally been to design the space system without regard to radiation, then to examine the need for possible modifications to meet the requirements for space radiation protection, considering the inherent protection provided by the mass of the baseline system. Possible modifications have included the following:

- Improvement of the intrinsic radiation hardness of critical items by choosing other materials or components
- Improvement of the protection provided by the mass of the system by modifying the configuration or by rearranging the interior
- Changes in the mission profile to reduce the radiation encountered
- Provisions for unscheduled (orbital) mission termination in the (uncertain) event that a dangerous solar cosmic-ray environment occurs
- Addition of material to serve as radiation shielding.

This has been the approach to space radiation protection for all manned space vehicle programs to date; special provisions for radiation shielding were not necessary for these systems. Generally, the same approach has also been taken for unmanned systems; exceptions include special cases such as shielding sensitive, exposed components like

solar cells, and instrumented payloads which involve shielding as an integral part of the instrumentation design (e.g., radiation detectors). However, future missions of longer duration and involving greater exposure to space radiation will require design of radiation protection into the system from the beginning. This is particularly true for manned interplanetary missions.

Because it is impossible to expose sizable systems to a true simulation of the space radiation environment with present accelerator and beta-irradiation facilities, the analysis and design of a space vehicle for space radiation protection must rely heavily on theoretical methods. The major factors involved in space radiation protection, in decreasing order of the uncertainty they usually introduce, are as follows:

- Space radiation environment encountered during the mission
- Maximum allowable doses
- Distribution of mass providing protection
- Methods of radiation transport and dose analysis.

The definition of the space radiation environment ordinarily introduces by far the greatest part of the overall uncertainty in the prediction of radiation doses. The definition of maximum doses that can be tolerated usually ranks as the next largest source of uncertainty, particularly for astronauts because both the acceptable and incurred risks are ill defined. In large and geometrically complex systems, such as manned spacecraft, the uncertainty in the mass distribution of the system usually introduces the next largest uncertainty in the radiation doses. This uncertainty is greatest for lightly shielded vehicles and for radiation environments with transmissions that are sensitive to material thickness (i.e., proton fluxes with predominantly low-energy particles, or soft energy spectra, and electrons). Theoretical methods now available for determining radiation doses are the most accurate element for geometrically simple, well-defined problems. The greatest source of error in analytical methods is introduced by the geometrical complexity of real systems. Because it is difficult to identify accurately and then specify the distribution of the mass of all components of a space vehicle in a form suitable for computations, the methods for radiation transport and dose analysis can, in some cases, introduce significant errors. This difficulty is greatest when time-dependent crew motion must be considered.

The basic procedure followed in determining space radiation doses shown in figure 1 includes the following:

- Definition of the space radiation to be encountered

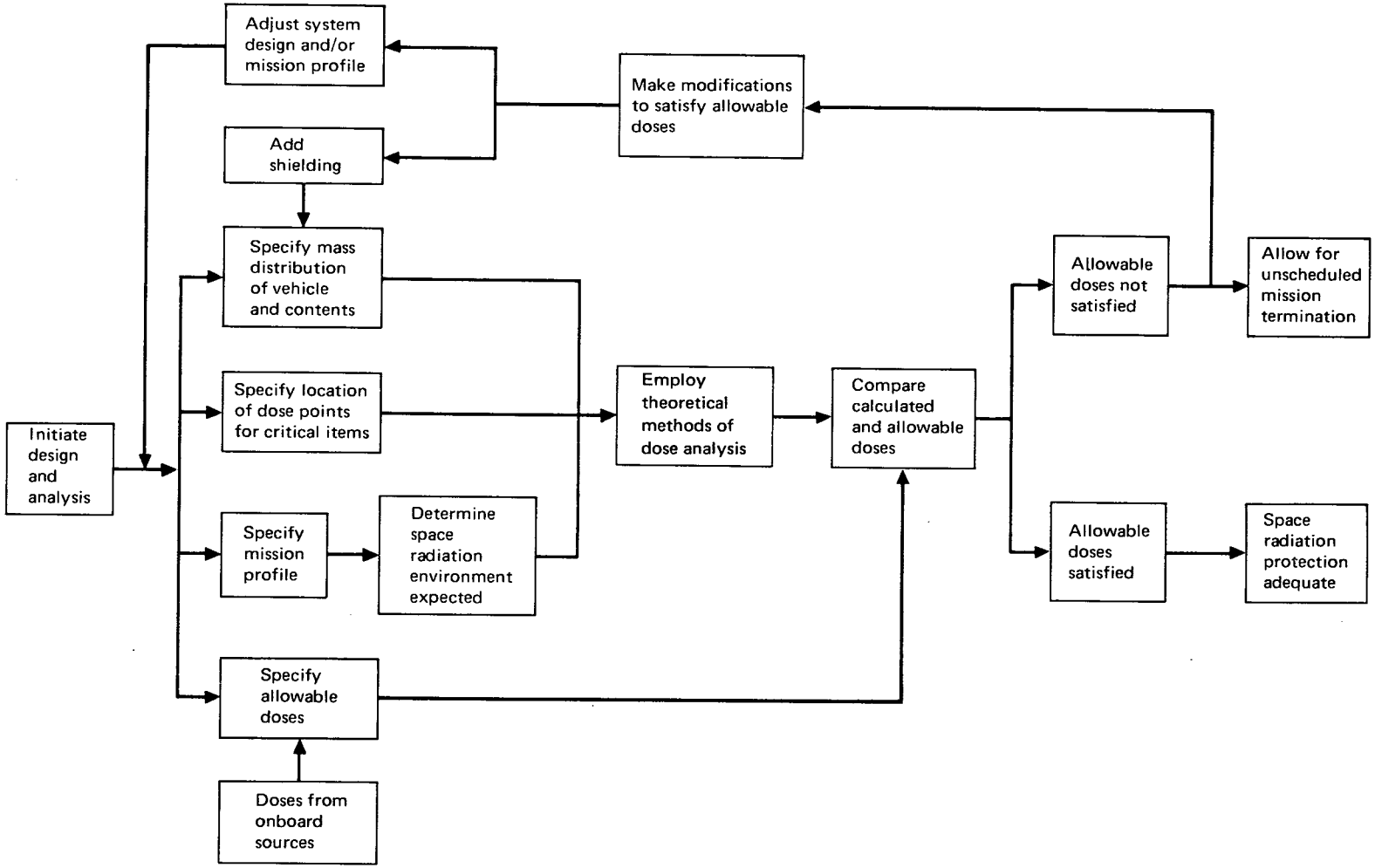



Figure 1. – Logic flow for the analysis and design of space radiation protection.

- Definition of the distribution of masses in the space vehicle (including occupants)

- Definition of the spatial and temporal relationship of each potentially critical item with respect to the rest of the system

- Use of theoretical methods of radiation transport to calculate the doses for each potentially critical item.

Doses caused by onboard radiation sources are accounted for independently. Figure 1 also shows the design requirement for satisfying the constraints imposed by the allowable doses, and the iteration loops involving the design alternatives for achieving this goal.

## 2.1 Space Radiation Environment

The penetrating space radiations that can have a significant effect on space vehicles are electrons, protons, and, to a lesser extent, heavier charged particles. Protons and electrons present the greatest hazard and are the most difficult to shield against because of their relatively higher intensity and greater penetrability. Alpha particles forming part of the solar cosmic-ray environment may be significant for situations in which little flux attenuation is provided because of their characteristically higher dose deposition. Energetic heavy nuclei comprising part of the galactic cosmic-ray environment can cause an amount of damage which is large, relative to their flux intensity, but their low flux intensity precludes the likelihood of their being of major importance (ref. 3). A succinct review of the space radiation environment important to radiation protection is given in reference 4.

### 2.1.1 Solar Cosmic Rays

Solar cosmic radiation important to radiation protection consists mostly of protons, with some alphas, emitted sporadically by the sun during some solar-flare events. The particle energies typically involve energy spectra that are softer than those associated with galactic cosmic rays and trapped protons. This source of radiation is significant for missions outside the geomagnetic field (i.e., earth-orbit missions at high latitude or very high altitude, and lunar or interplanetary missions), which can modify the energy spectrum and severely reduce the flux intensity (ref. 5). Earth shadowing also reduces the flux, by almost a factor of 2 for low orbits.

Solar cosmic rays are present for periods of up to several days. The directionality of the flux varies from highly anisotropic during onset of the event to nearly isotropic

later in the event. While the time-dependence of these events is highly variable, the events have a characteristic behavior (ref. 6). However, when an event will occur and what it will be like are not at this time usefully predictable, except in statistical terms. Attempts have been made to establish a correlation of sufficient strength to permit a reliable, long-term prediction of an event. Since most of the solar cosmic-ray dose received during a mission is likely to come from a single large event (ref. 7), such a correlation is particularly desirable for major events. Although there are correlations with sunspot number and other visibly observable conditions on the sun (e.g., refs. 8 and 9), no reliable method has been found. Consequently, the uncertainty in this environment is a major factor in establishing radiation protection requirements for long-duration missions outside the geomagnetic field.

From a practical standpoint, the most useful approach to this problem at this time is based on the assumption that the solar cosmic-ray environment is statistically random. The analyses reported in references 10 and 11 indicate that this assumption is consistent with the data obtained to date, and presumably it will apply to future solar cycles. Using such an approach, the probability of encountering a given solar proton environment during a mission of given duration can be estimated. Because little data exist, similar estimates for solar alpha particles would involve much more uncertainty. Other statistical analyses of the solar cosmic-ray environment are reported in references 7 and 12 to 15. References 6, 16, and 17 summarize the available data on observed solar cosmic-ray events. The most intense events of the 19th cycle which were measured and analyzed extensively are those of November 1960 (refs. 18 and 19).

### 2.1.2 Trapped Radiation

The earth and planets with a magnetic field similar to that of earth [Venus and Mars have no significant magnetic field and Jupiter has a strong field (refs. 20 and 21)] are surrounded by magnetically trapped radiation consisting of high-energy electrons and protons. The directionality of these particles is related to the orientation of the magnetic field; however, because the orientation of a space vehicle varies with respect to the magnetic field during the course of a mission, these particles are usually considered isotropic for the purpose of designing radiation protection.

Trapped radiation exists above the atmosphere and within most of the envelope containing the magnetic field. For earth, this varies from an altitude of approximately 200 km to beyond synchronous orbit altitude (35 900 km). High-energy electrons are contained in the inner and outer belts, which include the entire geomagnetic field. High-energy protons are restricted to the inner belt at altitudes of less than approximately 15 000 km; low-energy protons extend into the outer belt.

The earth's trapped-radiation flux intensity and energy spectrum are time-dependent because of solar activity. High-energy trapped proton fluxes are relatively stable, with variations of as much as a factor of 2 when solar storms occur (ref. 22). Trapped electron fluxes are much more variable, with changes of more than an order of magnitude in periods as short as minutes (refs. 23 and 24). The largest variations are at very high altitudes (e.g., around synchronous orbit) and at high geomagnetic latitudes. For missions longer than a few weeks' duration, the average flux is approximately constant. Although there are regular variations associated with the 11-year solar cycle, they are not yet resolved sufficiently to account explicitly for them in radiation protection design (ref. 24). In addition, the electron environment can be greatly enhanced by high-altitude nuclear explosions (ref. 25).

The earth's trapped radiation has been studied extensively and detailed descriptions are provided in references 22, 23, 24, 26, and 27; a rigorous discussion of the subject is contained in reference 28. The environment models have been incorporated into a computer program (ref. 29) for calculating the environment associated with any specified mission trajectory. A continuing effort is being made to refine these models. Reliability of the radiation environment data varies within the trapping region. The best data may be good to within a factor of 2 (e.g., refs. 27 and 30), generally at low and intermediate geomagnetic coordinates (low altitude, low geographic latitude). The greatest uncertainties occur at the boundaries of the trapping region, including the low-altitude region where atmospheric interactions are important.

### 2.1.3 Galactic Cosmic Rays

Galactic cosmic rays provide a continuous, essentially isotropic, radiation source consisting of about 85 percent protons, 14 percent alpha particles, and less than 1 percent heavier nuclei. This is the source most precisely known, and the uncertainty of its nature is relatively insignificant in the design of radiation protection.

The energies of these radiations are of sufficient magnitude that shielding against them and the secondary radiations they produce in shielding material is not practical. However, the intensity is small, and corresponds to a dose rate in free space (outside the geomagnetic field) that varies from approximately 8 rad (0.08 J/kg) per year during minimum solar activity to less than half this amount during maximum solar activity (ref. 31) at 1 AU ($149.598 \times 10^6$ km).

The flux intensity in the solar system is reduced by increased solar-storm activity by virtue of the interplanetary magnetic fields associated with solar storms (ref. 32). Also, the intensity varies with distance from the sun, although the nature and cause of the variation are uncertain (ref. 33).

The dose rate can be reduced by almost an order of magnitude by the geomagnetic field (ref. 34), and by as much as a factor of 2 by the earth's shadow for near-earth missions. Practical shielding thicknesses do not affect the dose rate by more than ±20 percent (ref. 31). The galactic cosmic-ray dose influences the design of radiation protection because it must be subtracted from the total allowable doses to determine the allowable doses from all other radiation sources. Reference 35 summarizes the state of knowledge of the galactic cosmic-ray environment.

## 2.2 Allowable Radiation Doses

Allowable radiation doses comprise the main specification to which radiation protection is designed. Allowable doses are determined on the basis of specialized knowledge of radiation effects, coupled with a philosophy or policy of what constitutes an acceptable risk to vehicle occupants and mission performance.

Penetrating radiations cause damage principally by the mechanisms of ionization and atomic displacement. Most of the data on radiation effects on materials and components do not provide definitive information directly related to specific applications in a space-radiation environment. Also, radiation effects are not always expressed in terms of consistent units or well-defined radiation environments. However, there is sufficient knowledge to provide meaningful specifications for many situations. Reference 36 presents a brief summary of the response of materials and components to space radiation. A NASA design criteria monograph on nuclear and space radiation effects on structural materials is planned. The Radiation Effects Information Center at Battelle Memorial Institute Columbus Laboratories is a central clearinghouse for radiation-effects data.

Space radiation damages biological tissue principally by ionization. The radiobiological responses of humans and the factors involved in manned space flight are detailed in reference 3. A major factor involved in establishing allowable doses for human occupants is the acceptable levels of short-term and long-term risks. This aspect is discussed in reference 37. Although there is no generally accepted or official position, examples of allowable doses that have been recommended for astronauts are given in references 37 and 38, and a brief summary of research related to this area is presented in references 39 and 40.

## 2.3 Dose Analysis

Current methods for the analysis and design of radiation protection can be used to estimate the radiation dose to space-vehicle components and occupants with a degree of accuracy consistent with present mission requirements. Because of the many

independent efforts and large amounts of information generated in recent years concerning radiation protection, the Radiation Shielding Information Center (RSIC) at Oak Ridge National Laboratory was formed as a central clearinghouse for shielding data and methods, including current information on space radiation protection. The RSIC is the most authoritative single source of information on available radiation shielding literature (refs. 41 and 42) and analytical methods; i.e., computer programs (refs. 43 and 44).

There are two general types of shielding applicable to protection against the charged particles that make up the space-radiation environment. These types are active shielding and passive shielding. Active shielding uses electric or magnetic fields to deflect the charged particles away from the spacecraft. The principle of passive shielding is simply to place mass between the radiation source and the receptor. When passing through mass, radiation is attenuated by atomic and nuclear interactions with the material.

Basically, the three methods of active shielding which have been investigated are (1) electrostatic, (2) magnetic, and (3) plasma. Electrostatic shielding does not appear feasible because of the large fields and power levels required (ref. 45). Magnetic shielding (refs. 46 and 47) and plasma shielding (ref. 48) are apparently advantageous relative to passive material shielding under certain conditions which depend upon vehicle size and the degree of protection required; their application, based on superconductivity, is not yet feasible. Therefore, passive material shielding represents the state of the art.

### 2.3.1 Proton Dose Analysis

For solar-proton and trapped-proton energy spectra, particle transport and dose transmission through shielding of less than approximately 20 g/cm$^2$ is primarily a matter of the loss of proton energy by direct ionization of the shielding material. The theory of this energy-loss mechanism or range-energy relationship is well known (refs. 49 and 50) and gives accurate results (refs. 51 and 52) except at very low energies (less than approximately 2 MeV). During the slowing down of primary (i.e., incident) protons, nuclear interactions with the shielding material create secondary nucleons (protons and neutrons). However, these secondary radiations, for typical solar-proton and trapped-proton energy spectra, affect the total absorbed dose by only approximately 10 percent for shield thicknesses of less than 20 g/cm$^2$ (refs. 53 and 54). It has been established that other proton-induced secondary radiations are usually unimportant. Secondary gamma radiation (ref. 55) is a possible exception in situations involving solar proton events with exceptionally large low-energy components.

The technology for analyzing the dose from primary protons is quite accurate when the mass distribution is defined accurately. For cases involving soft energy spectra and large shielding thicknesses, so that secondary radiations represent a large fraction of the total dose, confidence in computed results is not as high as when primary proton dose is dominant. However, for almost all practical spacecraft design situations, the uncertainty in secondary radiation dose is not highly significant because it represents only a small fraction of the total dose.

Current methods of analyzing proton dose produce reasonably consistent results (refs. 56, 57, and 58) which compare well in most cases with more detailed Monte Carlo calculations (refs. 59 and 60) that are not presently adaptable to design computations. Comparisons of Monte Carlo calculations with experimental data are presented in references 61 and 62. In particular, the straightahead approximation (i.e., no explicit angular treatment in the transport analysis), one of the basic simplifying assumptions used in design computations, has been shown to be sufficiently accurate for most design purposes (ref. 63). In addition, proton straggling (random deviation about the mean range) has been shown to be negligible (ref. 64).

There are a number of computer programs for proton-dose analysis in one dimension (e.g., refs. 54 and 65 to 68). These programs treat primary proton transport and secondary nucleon production and transport in one-dimensional configurations composed of laminated materials. All of them use the straightahead transport approximation. These programs are available to analyze systems that can be represented by one-dimensional configurations or to generate dose-attenuation kernels for three-dimensional analyses utilizing complex-geometry computer programs (e.g., refs. 65, 69, and 70).

Complex-geometry programs estimate the dose received at a given dose point by the following:

- Analytically tracing a large number of rays, each representing a solid-angle segment, from the dose point to the exterior of the space vehicle
- Determining the mass distribution along each ray and the corresponding dose attenuation based on one-dimensional calculations (i.e., the point-kernel approximation)
- Summing the dose contributions from each solid-angle segment to obtain the total dose from all directions.

For the complex-geometry programs to perform automatic sectoring and ray-tracing, the space vehicle and its contents must be represented by homogeneous spatial regions, bounded by mathematically defined surfaces.

For geometrically complex systems, approximations are made in representing the mass distribution to keep the magnitude of the effort within practical limits and to be consistent with the use of one-dimensional attenuation kernels. These approximations are the major source of error in the theoretical analysis; this problem is in addition to any lack of knowledge about the actual mass distribution. The uncertainty thus introduced for proton dose varies with the situation (i.e., with mass asymmetry, energy spectrum, degree of dose attenuation, etc.), but, based on limited quantitative data (e.g., ref. 71), it is estimated to be less than a factor of 2 for most practical situations.

References 55, 72, 73, and 74 summarize the technology of proton-dose analysis for space systems; reference 49 discusses the basic theory of proton interactions with matter. References 4 and 75 present discussions on the relative importance of some of the factors involved in estimating proton dose, based on comparisons with experimental data.

### 2.3.2 Heavy-Nuclei Dose Analysis

Heavy nuclei are charged particles more massive than protons and can be conveniently categorized as alpha particles and all heavier nuclei. The only significant source of nuclei heavier than alpha particles is the galactic cosmic-ray environment. Dose analysis behind significant shielding thicknesses for galactic cosmic rays heavier than protons is beyond the state of the art because knowledge about secondary radiations is insufficient (refs. 31 and 76). Measurements in the earth's atmosphere indicate that secondary radiations are extremely important in determining the galactic cosmic-ray dose rate, and in fact cause it to be approximately uniform, within ±20 percent, behind shielding of less than 100 g/cm$^2$ (ref. 31). Thus, from a practical design standpoint, heavy-nuclei dose analysis is limited to alpha particles associated with solar cosmic rays.

Alpha dose from solar cosmic rays may sometimes be significant behind shielding of only a few grams per square centimeter. Because of insufficient knowledge about alpha-induced secondary radiation, the state of the art is further limited to primary alpha-particle dose analysis. However, for solar cosmic rays, the rigidity (i.e., momentum per unit charge) spectra of alphas are similar to those of protons, while the particle fluence of alphas is no greater, and usually less, than that of protons (refs. 6 and 77). Therefore, alpha-induced secondaries are not likely to be as important as the proton-induced secondaries which always accompany them. Reference 76 summarizes the physics of heavy-nuclei secondaries from the standpoint of space radiation protection.

The interaction of alpha particles with matter is fundamentally the same as for protons (refs. 49 and 50), and all the procedures mentioned for analyzing primary proton dose

are directly applicable to the analysis of alpha-particle dose. Some existing computer programs may require modification to treat nuclei heavier than protons; however, the modification is minor since a simple scaling factor (ref. 49) relates all range-energy data for heavy charged particles to proton range-energy data (refs. 51 and 52), with negligible error compared to other sources of error that have been discussed.

The state of the art for primary alpha-particle dose analysis is essentially the same as for primary protons (i.e., calculated results are accurate to within 10 percent). Although knowledge of secondary radiations is not nearly as advanced for alphas as for protons, it probably does not significantly affect the overall state of the art of space radiation protection.

### 2.3.3 Electron and Bremsstrahlung Dose Analysis

In contrast to protons, the relatively small mass of electrons causes them to be deflected easily by collisions with atomic electrons and nuclei. This in turn causes them to produce bremsstrahlung (or X-rays), which is much more penetrating than the electrons. Also, the use of electron range-energy relationships (refs. 52 and 78) and the straightahead approximation to determine electron dose are consequently not as valid as for protons because of large variations of individual electron transmission about the average transmission (i.e., straggling). Although crude estimates of electron transport and dose can be made on the basis of the practical or effective range (ref. 49), these estimates are generally too high. The error ranges from negligible for zero shielding to an order of magnitude or more as shielding thickness increases (ref. 54).

Several electron Monte Carlo analytical schemes have been developed that are capable of performing accurate and detailed electron-transport analysis in one dimension (e.g., refs. 66, 79, 80, and 81) and in two or three dimensions (ref. 81). The use of these programs for practical shield design is time consuming; therefore, Monte Carlo calculations have been performed to generate parametric, one-dimensional, electron transmission data (ref. 82) for application to the point-kernel analysis of three-dimensional systems. Application of the point-kernel method to electrons is exactly analogous to that discussed for protons.

A summary of experimental data on electron transmission is given in reference 83; comparisons with theory are given in refs. 79 and 83.

Because trapped electrons are stopped by relatively thin shielding [the practical range is approximately $\frac{1}{2}$ g/cm$^2$ per MeV ($1.603 \times 10^{-13}$ J) of energy], the bremsstrahlung dose is often dominant over the electron dose because of the greater penetrability of bremsstrahlung. Thus, in some cases it is an important radiation protection

consideration. A comprehensive review of bremsstrahlung interaction is given in reference 84; recent detailed experimental data on bremsstrahlung production are presented in references 83, 85, and 86; comparisons with theory are given in references 79, 83, and 86.

The theory of electron bremsstrahlung production and its transport through matter is sufficiently accurate for the design of space radiation protection. As in electron transport, parametric Monte Carlo analyses of bremsstrahlung transport (ref. 87) are useful for generating dose-attenuation kernels for application to the design of radiation protection. Monte Carlo codes for performing detailed analysis of bremsstrahlung production and transport are described in references 80 (one-dimensional analysis) and 81 (one-, two-, or three-dimensional analysis).

As in the case of protons, there are design-oriented computer programs for economically performing electron and bremsstrahlung dose analysis (e.g., refs. 54, 65, and 66) in one-dimensional laminated shields. These programs are suitable for parametric studies and can be used with complex-geometry computer programs (e.g., refs. 65, 69, and 70) to analyze three-dimensional configurations. Analysis of electron and bremsstrahlung dose using these programs is sufficiently accurate for most design situations. The greatest uncertainty is in the use of one-dimensional electron transmission data to calculate electron dose in geometrically complex systems.

Uncertainty in the results of dose analysis generally increases as the geometrical complexity of the system increases. The uncertainty is usually greater for electron dose than for bremsstrahlung dose. For analyses based on the point-kernel method, electron dose may be in error by a factor of 2 or more (ref. 88); results of explicit Monte Carlo analyses provide the greatest achievable accuracy.

References 72, 73, and 89 summarize the technology for the analysis of electron and bremsstrahlung radiation protection; reference 89 presents an overall summary. Reference 90 presents a comparison of the results of the analyses obtained with several electron transport codes.

## 2.4 Shielding Design

The foregoing discussion has covered the state of the art for determining the radiation dose when a completely specified set of conditions is given. For the more general objective of shield design, two approaches are available. The first and more common approach is the iterative analysis of progressively improved designs; the second involves direct numerical optimization.

The first approach can be tedious, but it is applicable in principle to any level of system complexity and dose-analysis sophistication. The second approach is generally limited to the point-kernel method utilized by complex-geometry programs because it is impractical to use more exact methods in an automated or semiautomated optimization procedure.

The second approach of direct numerical optimization is particularly appropriate for geometrically complex systems with many parameters and multiple nonlinear constraints. Although computer programs of various degrees of sophistication have been developed for handling such problems, few have been published in the open literature. This approach is particularly appropriate for proton and alpha shielding because the point-kernel method is rather accurate for protons and alphas, even for highly heterogeneous systems. A program using the second approach is described in reference 91. It handles multiple time-dependent space- and onboard-radiation sources, generalized quadric geometry, multiple potential shield regions (including split shields that can be located on the walls of the crew compartment, on the walls of a biowell, and on mobile astronauts), and multiple dose constraints (based on multiple body-organ dose criteria and the specified time-weighted positions of occupants of the crew compartment). The inherent shielding worth of the unshielded vehicle is accounted for, and, for a minimum mass system, all shield dimensions are determined by automatic iteration. The limitations of this program are the same as those of the state of the art of complex-geometry dose analysis.

Unclassified examples of radiation analysis and shield design for complex systems are given in references 91 and 92.

## 2.5 Testing

Existing particle-accelerator and radioisotope facilities do not have the capability of simulating the space radiation environment in terms of energy spectrum or capability of accommodating sizable exposure areas. Consequently, the state of the art for testing space radiation protection is severely limited. Several experimental approaches have been considered, but no generally acceptable criteria for applying them to the testing of specific system designs have been defined. The approaches considered are as follows:

- Measurement of radiation transport through representative space-vehicle structures or components

- Measurement of the mass distribution of the space vehicle

- Unmanned experiments launched into space to establish experimentally the separate and combined uncertainties caused by the radiation environment and theoretical methods of dose prediction

- Instrumented flight tests of a space vehicle to eliminate the combined uncertainties associated with the trapped radiation environment, mass distribution, and theoretical methods of dose prediction.

Except for the last approach, these do not represent system testing in the usual sense, but are attempts to reduce experimentally the uncertainty involved in the radiation protection design process. An excellent summary of the status of the last two approaches is given in reference 4.

### 2.5.1 Measurement of Radiation Transmission

Although measurements have been made for individual components and for instrumented research probes, few have been made in direct support of a space-vehicle project. Some measurements of this kind were made early in the Apollo program.

### 2.5.2 Measurement of Mass Distribution

Measurements of the mass distribution have been made for the Apollo command module. Measurements have also been made for Gemini, but not as part of the normal development test program. In all cases, a gamma-probe device was used (ref. 93). Comparisons of the difference between calculated doses based on the estimated mass distribution and calculated doses based on the measured mass distribution indicated that the results based on the estimated mass distribution were high by a factor of 2.7 to 3.5 for Gemini, and by a factor of 1.5 to 1.7 for the Apollo command module (ref. 94). The range in the factors is caused by the several different proton environment models that were analyzed to assess the influence of energy spectra on the comparisons.

### 2.5.3 Unmanned Experiments

Unmanned experiments have been conducted as research projects (refs. 75, 95, and 96). The mass distributions of the systems were accurately known. Comparisons between theoretical predictions and measurements showed that the only serious discrepancy was caused by insufficient knowledge of the space-radiation environment. For example, reference 94 indicates that for thin shielding (less than 1 $g/cm^2$), the electron and proton environments described in references 23 and 26 resulted in calculated doses that in most cases disagreed with measured values by approximately

±40 percent. For greater shielding thicknesses (3 to 4 g/cm$^2$), the calculated proton dose was low by a factor that varied from approximately 2 to 10, depending upon the magnitude of the apparent error in the model environment energy spectra.

### 2.5.4 Instrumented Flight Tests

Space vehicle flight tests have been made which included onboard radiation detectors. Comprehensive radiation protection analyses based on inflight data have, for Project Mercury and the Gemini program, been made only for data gathered during manned operational missions (e.g., refs. 97, 98, and 99). However, for the Apollo program, the unmanned flight tests of Apollos 4 and 6 were instrumented and the measurements analyzed. A review of inflight dosimetry is given in reference 4.

## 3. CRITERIA

The space vehicle shall be designed to withstand the space radiation environment expected during the mission, without unduly endangering mission success or exceeding acceptable risk to astronauts. Sufficient space radiation protection shall be provided so that the specified allowable radiation dose and/or dose-rate criteria are not exceeded.

## 3.1 Space Radiation Environment

The space radiation encountered during the mission shall be determined on the basis of the mission profile (including date) and available descriptions of the space radiation environment. Radiation sources to be accounted for are solar cosmic rays, trapped radiation, and galactic cosmic rays. The uncertainties in significant parameters (e.g., flux intensity, energy spectrum, and temporal variations) characterizing each radiation source shall be accounted for.

## 3.2 Allowable Radiation Doses

Allowable radiation doses shall be established for all radiation-sensitive materials and components included in the space vehicle. The allowable doses shall not exceed amounts that would result in excessive radiation damage to the materials or components, taking the radiation source type and energy spectrum into consideration. Allowable space radiation doses shall reflect the presence of onboard radiation sources. The allowable doses shall be expressed in terms of explicitly defined units. Both dose rate and mission-integrated dose shall be considered.

## 3.3 Dose Analysis

Analysis of the doses and dose rates for each potentially critical component or system shall, when practical, account for the following factors, as applicable:

- Spectral, temporal, and directional characteristics of each primary and secondary radiation involved
- Spatial distribution and composition of the space-vehicle mass and its contents, including occupants
- Time-dependence of significant masses and their locations (e.g., occupants, propellant, stores, equipment, and jettisonable structure)
- Appropriate relationships which express allowable doses in terms of radiation fluences
- Finite extent of surfaces or volumes of potentially critical components and systems
- Estimates of the uncertainties in calculated critical doses and dose rates.

## 3.4 Shielding Design

Shielding shall be provided if the inherent protection afforded by the space vehicle is not sufficient to prevent the allowable radiation doses and dose rates from being exceeded for the duration of the mission.

If radiation shielding is required, it shall be designed to ensure environmental compatibility and structural adequacy under all conditions of combined radiation, thermal, and mechanical environments.

## 3.5 Testing

When analytical results are based on data that have not been demonstrated to be adequate, the data shall be confirmed or modified by tests that simulate the flight conditions as closely as possible.

# 4. RECOMMENDED PRACTICES

The analysis and design of space radiation protection are usually iterative processes in which the analyst and the designer are confronted by alternatives at the beginning of

each cycle (fig. 1). To integrate radiation protection considerations into a space vehicle, it is recommended that such considerations be included at the initiation of the conceptual design and accounted for throughout the design and development phases.

The initial cycle determines if the space-radiation environment is likely to constitute a serious hazard. If it appears that a serious hazard may be encountered, a dose analysis of the proposed vehicle is then conducted to determine the total dose and/or dose rate to potentially critical components. This analysis is based on preliminary definitions of the vehicle configuration and mission profile.

If the preliminary (conservative) estimates of the limiting allowable doses for the components are not exceeded, it may be tentatively concluded that the inherent shielding provided by the vehicle is sufficient. When significant changes are made to vehicle configuration or mission profile, a dose analysis should be conducted to determine if the prior conclusions regarding the shielding provided by the vehicle are valid. In the final stages of design, when it is unlikely that significant changes will be made in the vehicle configuration or mission profile, a final analysis should be performed to demonstrate that no allowable doses are exceeded.

If the results of the preliminary dose analysis show that the inherent shielding provided by the vehicle is inadequate, a choice must be made during the second cycle (and subsequent cycles) between providing some form of radiation protection or restricting the mission profile. Subsequent analyses should be performed to assess changes to the vehicle configuration and to the mission profile, and a final analysis should be made to substantiate the adequacy of the radiation protection.

During analysis and design, it is recommended that sufficient experimental verification of theoretical results be made to ensure that the uncertainty associated with the space radiation hazard does not constitute an unacceptable burden to mission risk and to vehicle reliability requirements.

## 4.1 Space Radiation Environment

Radiation sources that should be accounted for are solar cosmic rays, trapped protons and electrons, and galactic cosmic rays. Each of these sources is a function of the mission date, mission duration, and mission trajectory, and should be defined specifically for each mission profile. Emphasis should be placed on flux intensity and energy spectrum, the parameters of primary importance; of lesser importance are flux directionality and time dependence. Estimates should be made of the uncertainties in the environment so that their influence on radiation hazard and mission risk can be evaluated.

### 4.1.1 Solar Cosmic Rays

The projected solar cosmic-ray hazard can be expressed meaningfully only in statistical terms. Thus, radiation protection should be designed on the basis of the estimated probability of encountering a specified environment; the probability estimate should include the solar-cycle effect. For probability values or confidence levels close to unity, the possibility of encountering events that are larger and more frequent than previously observed must be accounted for (refs. 11 and 100).

For missions in the proximity of planets or their satellites, an isotropic solar-cosmic-ray flux is reduced by a factor corresponding approximately to the fractional solid angle the bodies subtend. Another geometrical factor is the (assumed) average inverse-square relationship with respect to the distance from the sun. Although these factors are usually relatively minor, they should generally be accounted for.

In the vicinity of the earth, the shielding effect of the geomagnetic field should be accounted for. Only crude estimates can be made on the basis of a geomagnetic dipole approximation (refs. 20 and 101). Accurate estimates require an accurate representation of the geomagnetic field as related to the mission profile (ref. 5), including modification of the field by the solar cosmic-ray event (ref. 66).

For situations involving shielding thicknesses of less than several grams per square centimeter, alpha particles should be included in the environment definition (refs. 6 and 77).

### 4.1.2 Trapped Radiation

For the earth's trapped radiation environment, the data and models contained in NASA SP-3024 (refs. 22, 23, 24, 26, and 27), or equivalent data and models, are recommended. Except when crude estimates are acceptable, a computer program equivalent to that described in reference 29 is recommended to obtain trajectory-dependent trapped radiation environments.

### 4.1.3 Galactic Cosmic Rays

In the vicinity of the earth (or other bodies), the effect of shadow shielding and the shielding effect of the geomagnetic field should be taken into account in a manner similar to that employed for solar cosmic rays. However, for galactic cosmic rays, the quiescent geomagnetic field and measured data on cutoff rigidity (ref. 102) are appropriate. The reduction in the absorbed dose rate caused by these effects is indicated in figure 8 of Section 4.3.1. In addition, the effect of the solar cycle should be accounted for with respect to mission date (fig. 7, Sec. 4.3.1).

## 4.2 Allowable Radiation Doses

Available data on radiation effects and a survey of the categories of all significant materials and components in a space vehicle should be used to identify potentially critical items. For these items, maximum allowable doses (and dose rates) should be established. An estimate should be made of the uncertainties in the allowable doses so that their influence on radiation protection requirements and mission risk can be evaluated. Allowable doses from space radiation must reflect the dose received from onboard radiation sources (Sec. 4.4).

Where applicable, the rad unit (0.01 J/kg) (ref. 1), which refers to energy absorption, should be used. When a radiation-effects criterion is based on a calculated quantity other than energy absorption, the relationship between the calculated quantity and the radiation type and energy spectrum must be explicitly defined. Solar-cell damage (ref. 103) and biological response (refs. 1 and 104) are two examples sometimes involving the latter. Unless otherwise specified, definition of the rem dose-equivalent unit referred to in the literature is based on the quality factor defined in reference 104.

There are no generally accepted policies or procedures allowing definitive recommendations on how to establish allowable doses. However, it is recommended that the planned NASA design criteria monograph on nuclear and space radiation effects on structural materials and the information available through the Radiation Effects Information Center at Battelle Memorial Institute Columbus Laboratories serve as guides relative to materials and components; for establishing allowable doses for crew members, the data and philosophy expressed in references 3 and 37 are recommended.

## 4.3 Dose Analysis

The formal expression for calculating radiation dose is

$$D = \int \phi(E) W(E) dE \qquad (1)$$

where D is the dose; $\phi(E)$ is the fluence at a dose point, expressed as a function of energy, E; and W(E) is an energy-dependent weighting function. At a given dose point, $\phi(E)$ is determined by the external radiation environment, as modified by the mass surrounding the dose point. If the dose is expressed in rad, W(E) is the stopping power (refs. 51, 52, and 78) for charged particles or the energy-absorption coefficient (ref. 105) for bremsstrahlung, expressed in appropriate units. If the dose (equivalent) is expressed in rem, W(E) also includes the quality factor (refs. 1 and 104). Evaluation of this equation at points of interest throughout a space vehicle is the basic objective of dose analysis.

As discussed in Section 2.3, to account explicitly for the radiation coming from each direction, the dose at a point within the mass distribution making up a space vehicle should, in general, be determined by using the point-kernel method. The dose is computed by an appropriate summation of the contributions from all directions, and can include the effect of flux anisotropy.

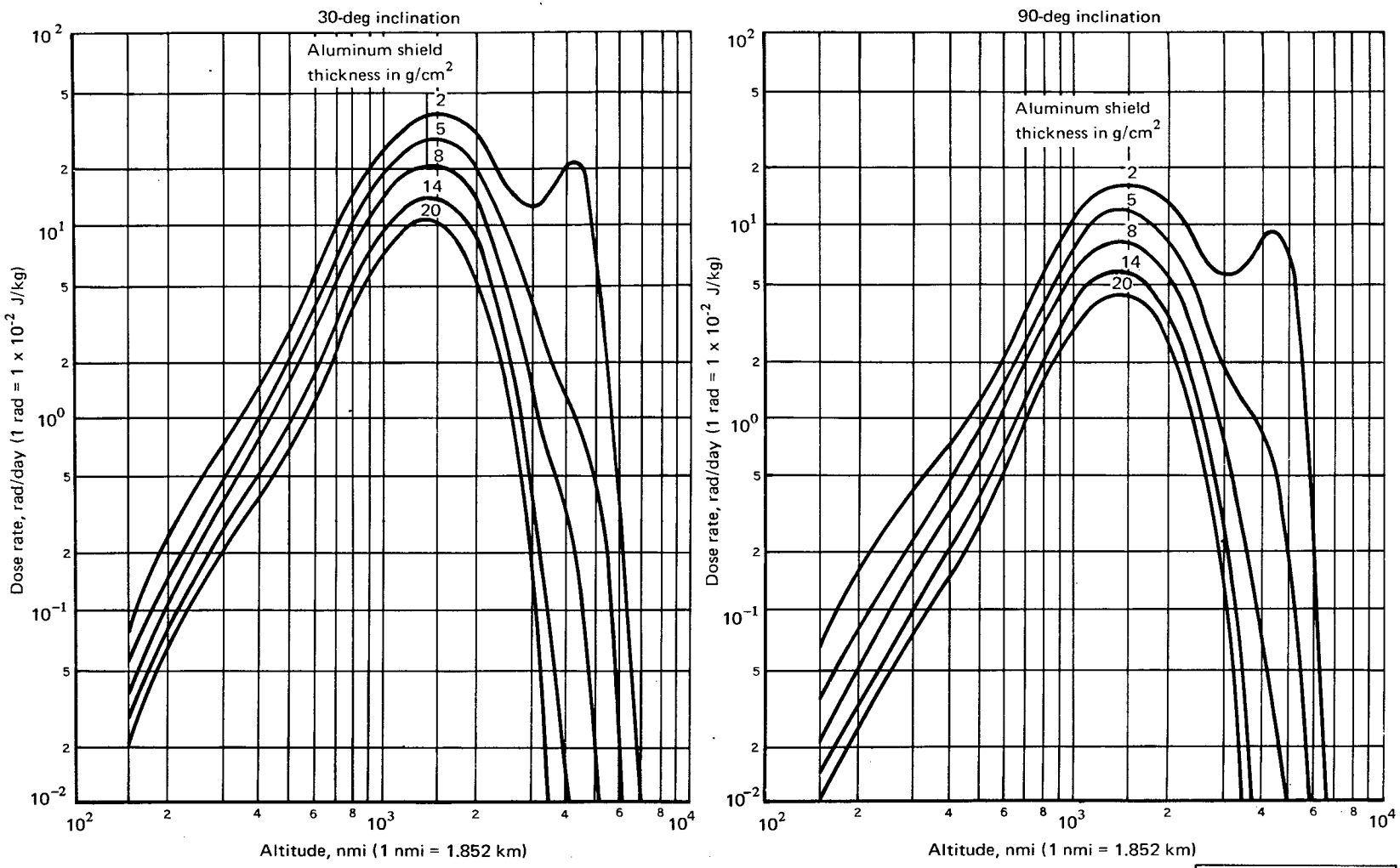
For accurate and efficient dose analysis, the use of complex-geometry computer programs (e.g., refs. 65, 69, and 70) are recommended. Preliminary dose estimates can sometimes be made satisfactorily without the aid of these programs by making simplifying assumptions regarding the geometrical representation of the space system. However, extreme caution must be exercised in making such estimates and in applying the results.

To perform dose analyses for any geometrical representation, the basic requirement is the ability to obtain appropriate (one-dimensional) dose-attenuation kernels. The following sections discuss the recommended procedures for performing the one-dimensional dose analyses required to generate dose-attenuation kernels. In addition, parametric curves of absorbed dose versus shielding thickness are presented for specific situations.

### 4.3.1 Proton Dose Analysis

When secondary nucleons are of significant consideration (e.g., refs. 53 and 54), computer programs (e.g., refs. 54 and 65 to 68) are necessary to obtain accurate dose estimates. For shielding thicknesses for which primary proton dose is dominant, the dose can be estimated by considering primary proton ionization only (i.e., no nuclear interactions). This approximation is valid for shielding that is not too thick; the range of thicknesses for which it is valid depends on the proton energy spectrum, the dose response used, and the desired accuracy. Soft energy spectra and a dose response which emphasizes secondary neutrons (e.g., rem) tend to decrease the shield thickness for which primary proton dose is dominant. For most trapped proton and solar proton spectra, the absorbed dose can be determined within approximately 10 percent for shielding thicknesses less than 20 g/cm$^2$ (ref. 53). For this range of shield thickness, either the computer programs referred to above or analytical expressions similar to those presented in references 34, 106, 107, and 108 are recommended.

Figure 2 presents the trapped-proton dose rate as a function of aluminum shield thickness and orbit altitude for 30-deg and 90-deg orbit inclinations. Similar curves for 0- and 60-deg inclinations are presented in reference 109. The curves are based on the orbit-integrated proton environment for circular orbits taken from reference 26. Figure 2 does not indicate the fact that the trapped-proton dose rate for low-altitude orbital




Note:
• After reference 109

Figure 2. – Trapped proton dose rate as a function of aluminum shield thickness and circular orbit altitude.

missions is highly periodic (ref. 109). This is caused by the highly localized spatial distribution of the trapped environment in the South Atlantic Geomagnetic Anomaly (ref. 28).

Figure 3 illustrates the free-space solar proton dose as a function of aluminum shield thickness and the estimated probability of not exceeding a given dose within a one-year mission during solar maximum at 1 AU (149.598 x $10^6$ km). The curves are based on data obtained during the 19th and 20th solar cycles. The same curves describe the expected dose for missions during solar minimum, except the doses are a factor of 10 to 20 lower than those indicated in figure 3, depending on the probability (ref. 11).

Figure 4 presents dose-scaling factors for the curves in figure 3 as a function of mission duration. Although the curves in figure 4 are for solar maximum, similar curves describe the variation during solar minimum, except they are lower by as much as 20 percent (ref. 11).

Figure 5 shows the variation of solar proton dose with aluminum shield thickness and circular orbit inclination. The dose variation shown in figure 5 is expressed in terms of a dose-reduction factor based on the curves for the free-space dose versus shield thickness shown in figure 3. Figure 5 includes the shielding effects of the geomagnetic field and the mass of the earth. The curves are recommended for relatively low altitudes (up to several hundred kilometers).

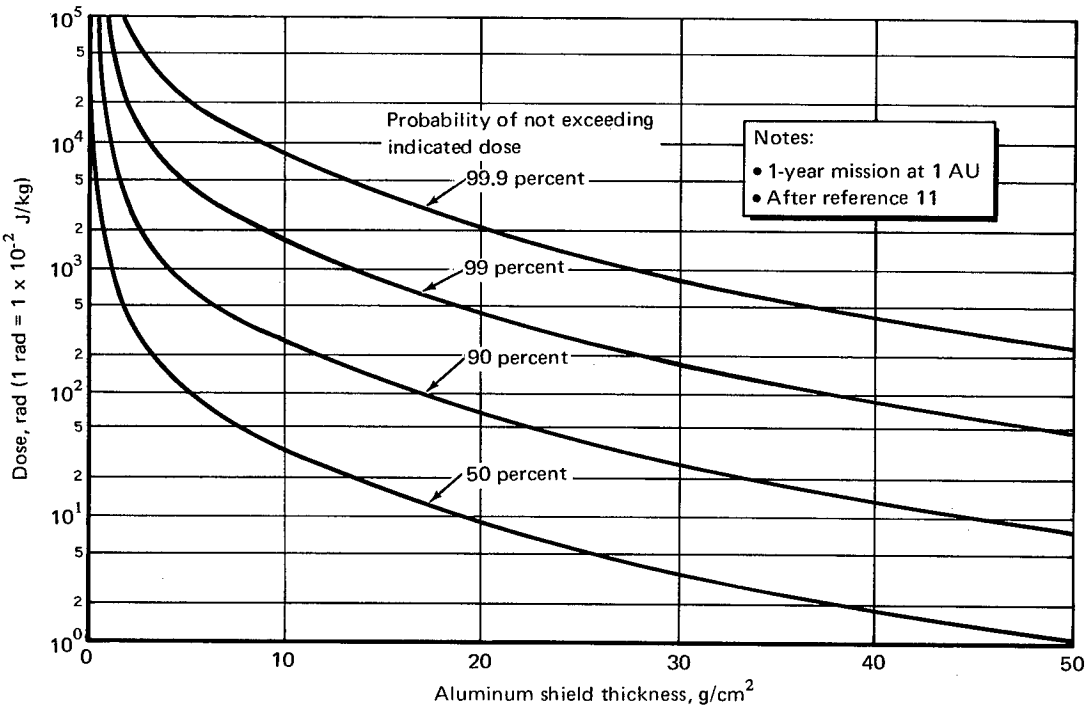



Figure 3. – Solar proton dose as a function of aluminum shield thickness and confidence level for solar maximum.

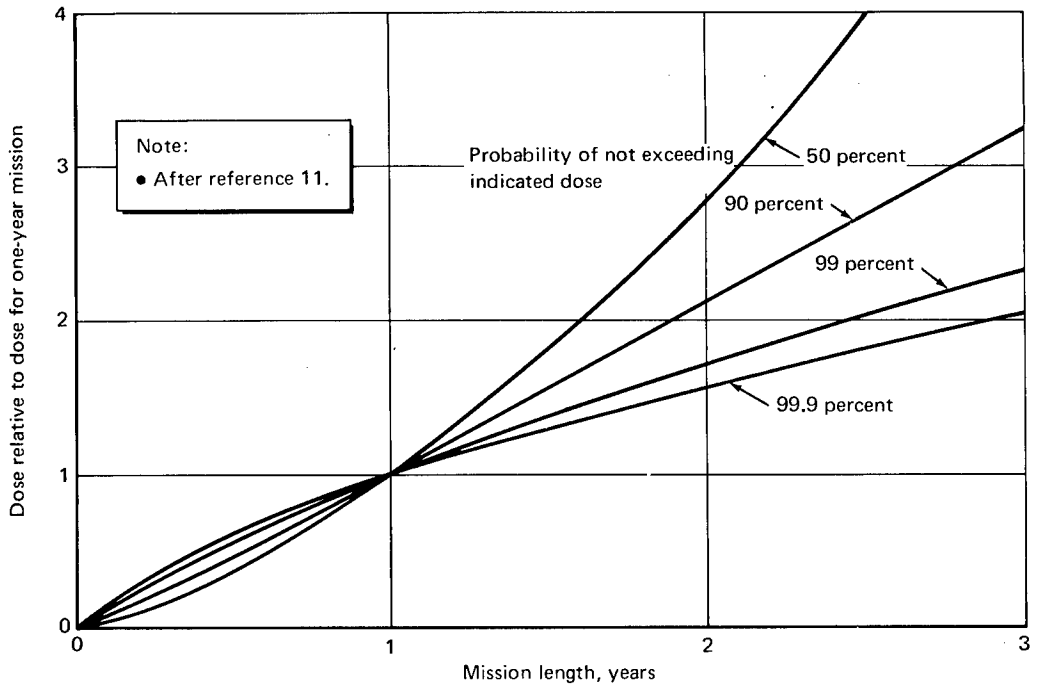



Figure 4. – Variation of solar proton dose with mission length for solar maximum.

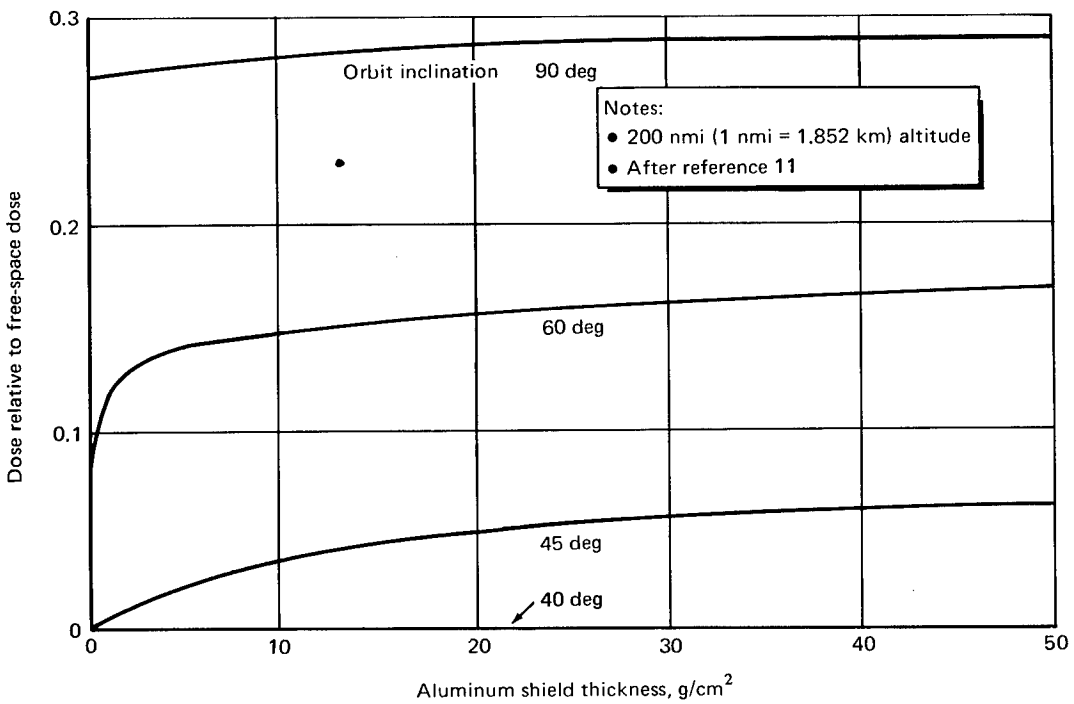



Figure 5. – Variation of solar proton dose with aluminum shield thickness and circular orbit inclination

The data in figures 2 and 3 can be applied to other shielding materials for shield thicknesses less than 20 g/cm$^2$ by expressing the actual shield thickness in terms of equivalent aluminum thickness, using the mass-weighted relative shielding-effectiveness data given in figure 6.

Additional parametric dose-attenuation curves are presented in reference 58 for various proton energy spectra expressed as exponential functions of rigidity.

All the dose curves discussed are for dose in tissue at the center of a spherical-shell shield; i.e., they account for no asymmetry of mass distribution about the dose point. For example, astronaut self-shielding will reduce skin and eye doses to approximately half the doses indicated (ref. 110).

For estimates of the galactic cosmic-ray dose, it is recommended that the results of measurements be used directly, rather than to rely upon analysis. Any attempt to calculate the galactic cosmic-ray environment in terms of detailed particle fluxes behind significant shield thicknesses will involve considerable uncertainty. Figure 7 gives the total galactic cosmic-ray dose rate at 1 AU (149.598 x 10$^6$ km), as a function of shield thickness. These curves are based on atmospheric measurements, as reported in reference 31. Although the actual shield material involved in the measurements is air, the curves are approximately correct for shielding materials whose average atomic weight is not too dissimilar to that of air (ref. 76).

Figure 8 shows the (unshielded) galactic cosmic-ray dose rate, relative to the dose rate in free space, as a function of circular orbit inclination. The curve includes the

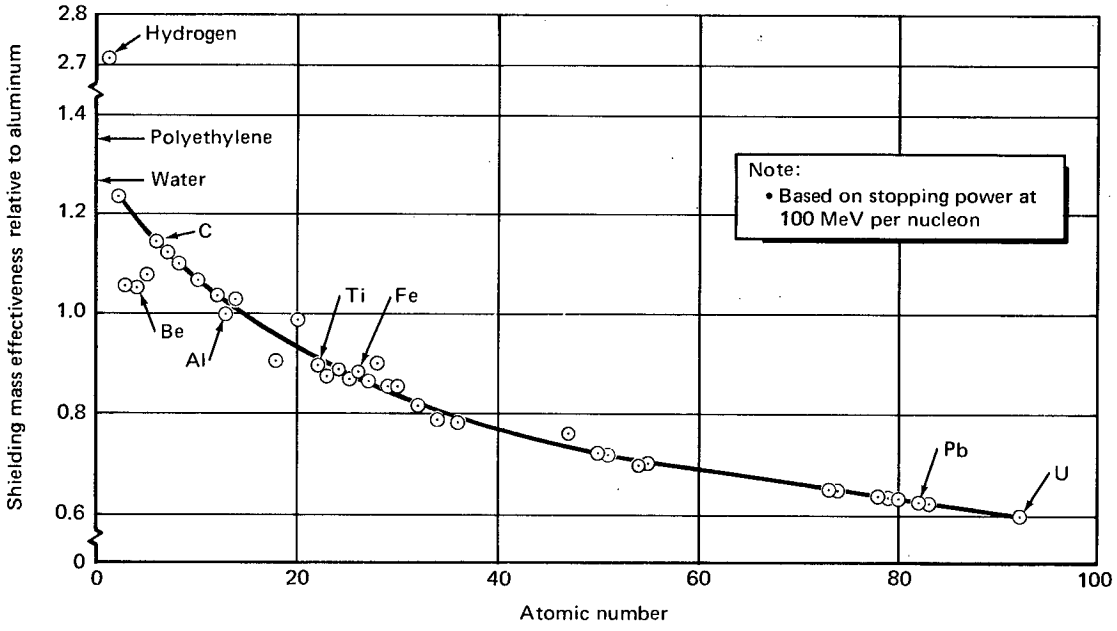



Figure 6. – Relative shielding effectiveness for protons and alphas.

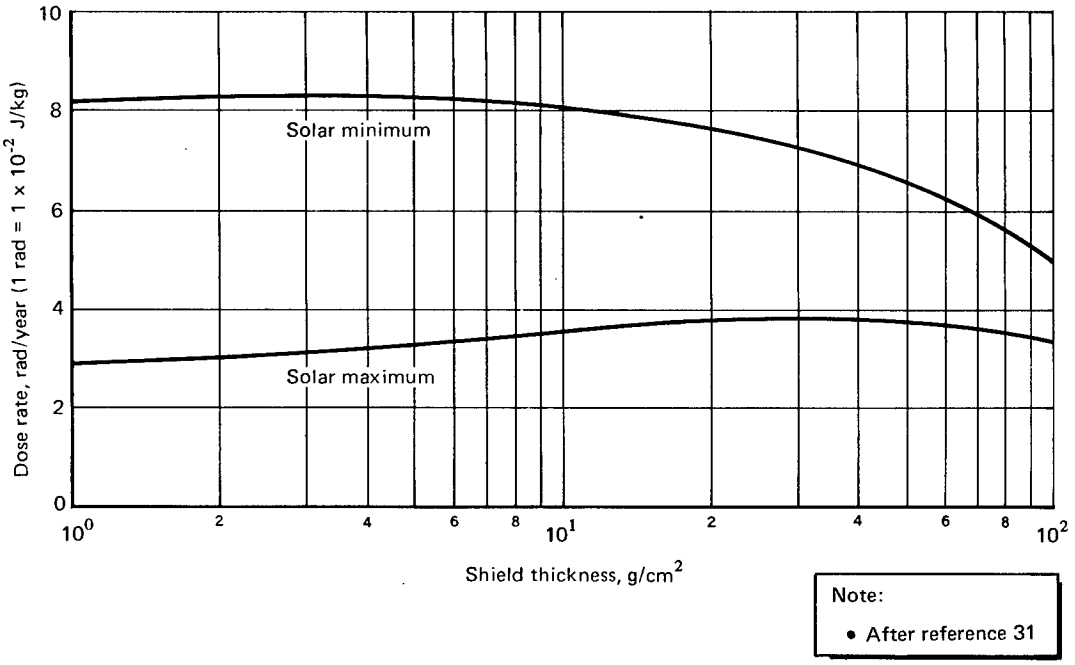



Figure 7. – Free-space galactic cosmic-ray dose rate at 1 AU.

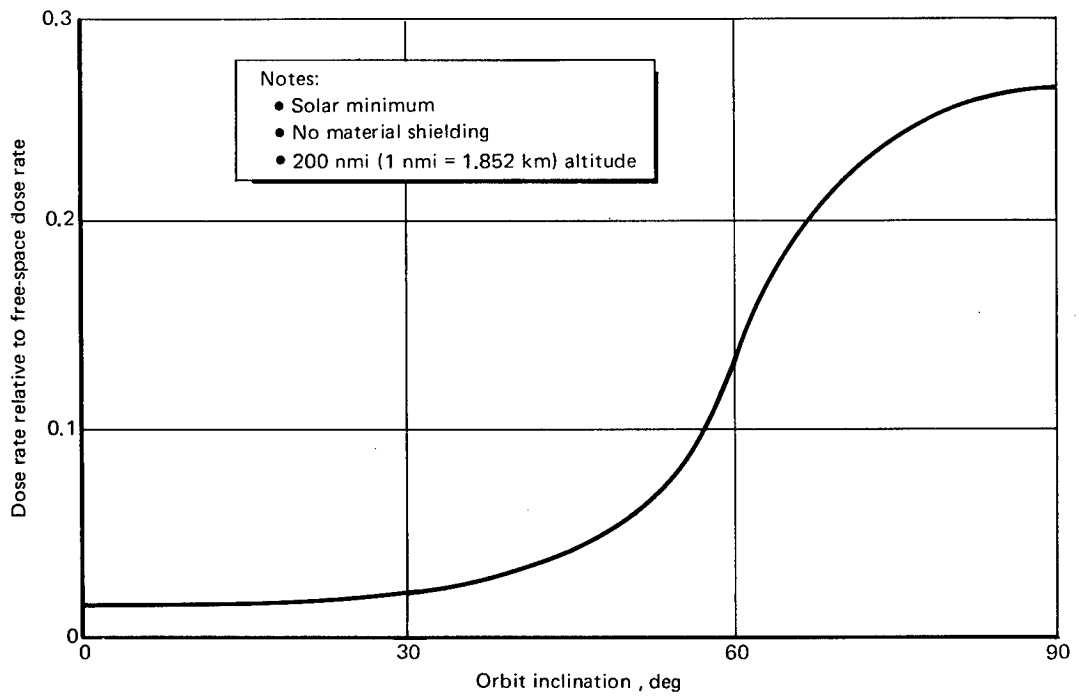



Figure 8. – Variation of galactic cosmic-ray dose rate with circular orbit inclination.

shielding effects of the geomagnetic field and the mass of the earth. The curve is based on calculational methods described in reference 111, the galactic cosmic-ray environment presented in reference 32 for solar minimum, and the relationship for cutoff rigidity given in reference 102. The dose-rate reduction will not be as great for solar maximum as indicated in figure 8 for solar minimum; the low-energy part of the galactic cosmic-ray energy spectrum is more uncertain for solar maximum than it is for solar minimum (ref. 35).

Figure 8 is recommended for relatively low altitudes (up to several hundred kilometers), and can be applied as a dose-reduction factor that is independent of shielding thickness up to approximately 20 $g/cm^2$. For higher altitudes, similar curves can be calculated using methods referred to in Section 4.1.3.

### 4.3.2 Heavy-Nuclei Dose Analysis

Alpha particles associated with solar cosmic rays are the only heavy nuclei which are both significant to space radiation protection and can be adequately analyzed for significant shielding thicknesses. Dose estimates for the heavy-nuclei component of galactic cosmic rays should be based on measured data, as discussed in Section 4.3.1.

The same methods recommended for primary proton dose analysis are recommended for primary alpha-particle dose analysis. Alpha-induced secondary radiations are probably not important for solar cosmic rays; analysis of such radiations is beyond the state of the art.

Parametric curves of dose versus aluminum shield thickness are illustrated in reference 58 for various alpha-particle energy spectra expressed as exponential functions of rigidity.

### 4.3.3 Electron Dose Analysis

An empirical fit to Monte Carlo calculations (ref. 82) gives analytical expressions for the number of normally incident electrons and their energy spectra, which are transmitted through slab shields of finite thickness. These or equivalent expressions are recommended to estimate the electron flux and energy spectrum at the center of a spherical-shell shield caused by an incident, isotropic, electron flux. The expression for number transmission is accurate to within approximately 10 percent for a single material (ref. 89). For laminated shields it is not as accurate (ref. 54) but is acceptable for most design purposes. Because the spectrum tends to flatten more than indicated, the accuracy of the expression for the transmitted energy spectrum decreases as shield thickness increases, but the effect on absorbed dose is small.

Since the analytical expressions are for monoenergetic, incident electrons, they are applied to a continuous energy spectrum by superposition of a number of discrete energy groups. For rough approximations (typically within a factor of 2 for absorbed dose), the electron stopping power can be assumed to be a constant [approximately 2 MeV per g/cm$^2$ ($3.206 \times 10^{-13}$ J per g/cm$^2$)], and the electron dose in rads is then proportional only to electron particle-fluence transmission.

Figure 9 describes trapped-electron dose rate as a function of aluminum shield thickness and orbit altitude for 30-deg and 90-deg orbit inclinations. Similar curves for 0- and 60-deg inclinations are presented in reference 109. These curves are for circular orbits and are based on the orbit-integrated electron environment estimated to exist around the year 1968 (ref. 23). The curves are to be interpreted in the same way as the curves in figure 2. Also, the periodic nature of the dose rate for low-altitude orbital missions is approximately the same as for protons. Parametric curves of dose versus aluminum shield thickness are given in reference 109 for various electron energy spectra expressed as exponential functions of energy.

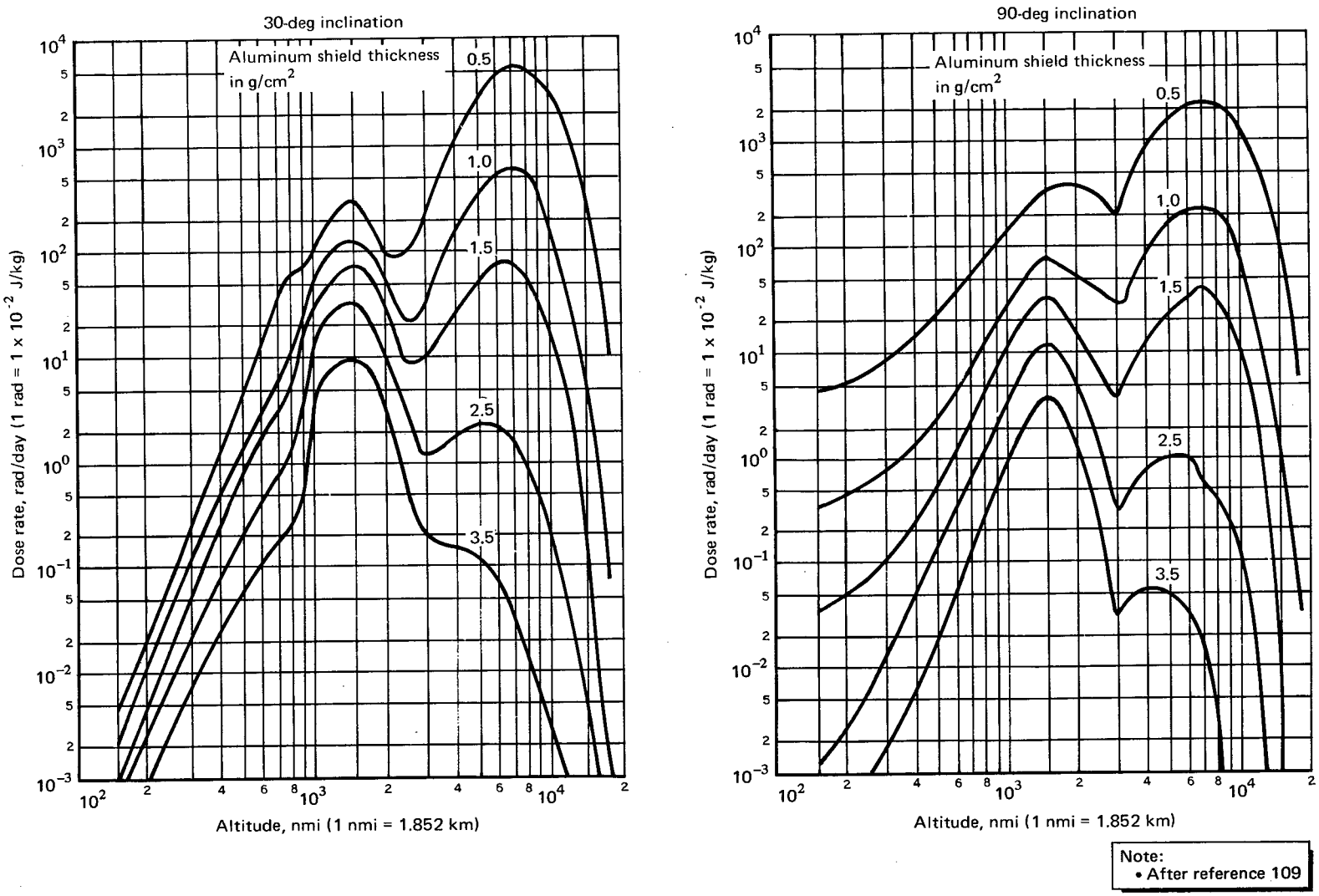
Computer programs recommended for design analysis (e.g., refs. 54, 65, and 66) use either the data discussed above or similar data based on experiment or other calculations (e.g., ref. 112). However, for quite specific situations requiring a high degree of accuracy, Monte Carlo programs may be desirable (e.g., refs. 66, 80, and 81). For typical design analysis, however, the design-oriented programs are adequate.

### 4.3.4 Bremsstrahlung Dose Analysis

The total forwardly directed bremsstrahlung energy fluence, I, created in a shield of atomic number Z by an isotropic, monoenergetic electron fluence of energy, E, is given by $I = CZE^2$. C is a slowly varying function of E and shield thickness (ref. 79). With I in MeV/cm$^2$ and E in MeV, C is approximately $4 \times 10^{-4}$ for targets whose thicknesses are comparable to the electron range. Bremsstrahlung energy spectra are defined by the empirically corrected theoretical expressions given in reference 84.

The bremsstrahlung dose at the center of a spherical-shell shield, caused by an incident, isotropic electron flux, is commonly estimated by using semiempirical expressions similar to that given above to define the bremsstrahlung source. The point-kernel method is then applied to estimate photon transport and dose transmission (refs. 87 and 105).

Figure 10 shows the bremsstrahlung dose for the same conditions and radiation environment as given for figure 9. Similar curves for 0- and 60-deg inclinations are illustrated in reference 109. The curves are to be interpreted the same as those of figure 9; also, the time-dependence of the bremsstrahlung dose rate corresponds closely




Note:
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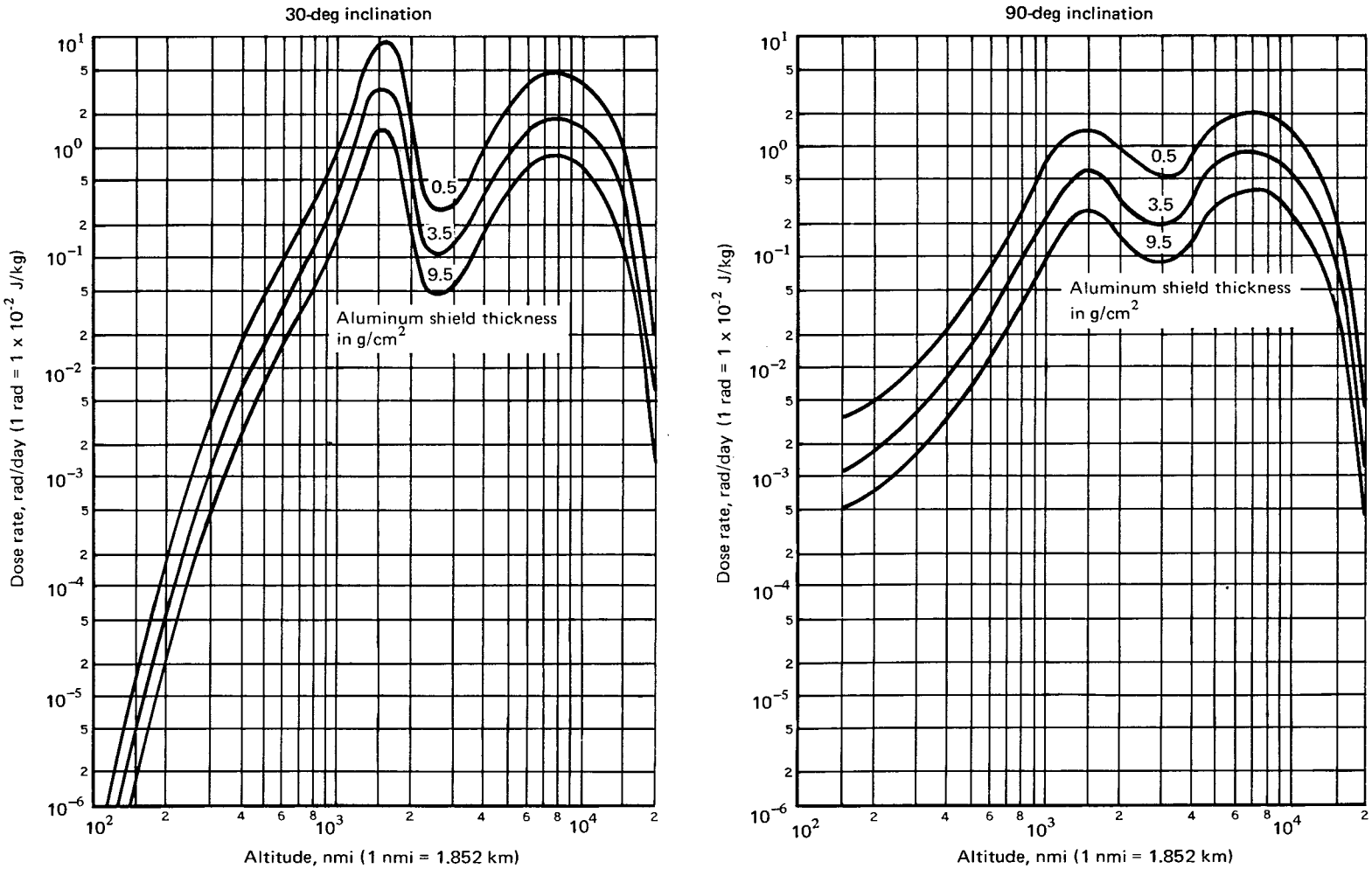
Figure 9. – Trapped electron dose rate as a function of aluminum shield thickness and circular orbit altitude.




Note:
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Figure 10. – Bremsstrahlung dose rate as a function of aluminum shield thickness and circular orbit altitude.

to that of electrons. Parametric curves of bremsstrahlung dose versus aluminum shield thickness are presented in reference 109 for various electron energy spectra expressed as exponential functions of energy.

Computer programs recommended for design analysis (refs. 54, 65, and 66) use either the methods discussed above or similar methods (ref. 112). To obtain a high degree of accuracy, Monte Carlo programs (refs. 80 and 81) may be desirable; however, the design-oriented programs are adequate for typical design analysis.

## 4.4 Shielding Design

When radiation protection is required, the following four alternatives should be considered:

1. Improve the intrinsic radiation hardness of critical items by other choices of materials or components.

2. Add mass to the vehicle structure (e.g., heavier pressure shell, meteoroid bumpers, structural members, and coverings).

3. Change the vehicle configuration or arrangement of its contents to promote better inherent shielding.

4. Add material whose sole function is to provide radiation shielding (e.g., local shielding of critical components).

For manned vehicles, these alternatives include the use of personal shielding for crew members and a biowell (storm shelter) that is a small shielded volume for short-term occupation by the crew. A biowell may be appropriate when a major portion of the potential radiation hazard is expected to result from solar cosmic rays. For manned systems, an onboard dose-monitoring and radiation-monitoring system is recommended (refs. 4 and 113). Such a system provides a method of determining the actual dose being received and allows preventive measures to be taken. Preventive measures may include the occupation of a biowell, restriction of extravehicular activities, or the termination of earth orbital missions at the onset of dangerous solar flare activity (ref. 114) or dangerous enhancement of trapped electrons.

The first two alternatives previously listed are self-explanatory. The third alternative usually involves straightforward dose mapping within the vehicle for a series of trial arrangements. From such an analysis, a reasonable approximation to optimality can be chosen. The effectiveness of this procedure can be enhanced by using the information generated on the directional characteristics of the flux intensities inside the vehicle. A

formal optimization procedure for these alternatives is not worthwhile in many cases, and is difficult for complex systems.

The fourth alternative is primarily a matter of the selection and placement of shielding material. The shielding placement is almost always the most important in determining shielding mass requirements. Either of the two general procedures discussed in Section 2.4 is recommended for determining shield placement. If a computer code is available that can model the problem realistically, it is preferred because of the greater accuracy and consistency (i.e., repeatability) of the results. In any case, the shielding placement problem begins with the identification of a number of defined, potential shielding locations (e.g., specific segments of the pressure shell and bulkheads, biowell walls, personal shielding, etc.), along with specified allowable doses and all the elements that enter into dose analysis. The basic procedure recommended is first to analyze the unshielded vehicle. If it provides inadequate protection, then, on the basis of geometrical considerations and dose-analysis information, discrete masses of shielding should be progressively added at the most advantageous locations until all allowable doses are not exceeded. Details of such a procedure are described in reference 91.

The selection of shielding materials depends on the particular considerations important in a given design. The most common design considerations that should be considered are shielding effectiveness, dual utility, radiation resistance, manufacturing cost, and structural strength.

The shielding effectiveness of a material (on a mass-per-unit-area basis) depends on the physical interactions involved and relates directly to the shield mass required to meet a given set of design criteria. Mass density plays a minor role in determining minimum shield mass (ref. 115). For protons and alphas, materials of low atomic number are more effective because they have greater stopping power and generate less secondary radiation. A good approximation to the relative shielding effectiveness of a material for proton and alpha shielding is the relative stopping power (fig. 6). The effectiveness of a combination of elements is determined on a mass-averaged basis.

The major material selection criterion that should be considered for electron shielding is the minimization of bremsstrahlung production; the higher the atomic number, the more undesirable bremsstrahlung is produced. Relative electron shielding effectiveness varies with atomic number, shield thickness, and energy (ref. 82); however, it is not strongly material-dependent.

Dual utility can result in significant weight reduction for space vehicles, and therefore should always be exploited as much as practical. For example, the judicious arrangement of spacecraft structure, equipment, and supplies maximizes the protection afforded, and a biowell surrounded by propellant can provide useful protection against solar cosmic rays before the propellant is expended.

Shielding should be designed to minimize the interference with space-system functions; for example, leak detection and repair, or occupant, component, and system performance.

The design of space radiation protection and the design of protection from onboard radiation (neutron and gamma ray) sources are separable for all practical purposes and can be analyzed independently. The only significant interface between the two is the division of the total allowable doses between the two kinds of sources. The coupling between the two kinds of sources, in terms of structural and configurational influences, is typically weak because of the large contrast between the penetrability and directionality of onboard sources compared to those of space radiation. It is possible for the division of allowable doses to be determined on the basis of minimum total shielding mass; however, in practice, for manned vehicles, the allowable doses allocated to onboard sources are arbitrarily set considerably lower than those allocated to space radiation because of the greater confidence in defining onboard sources.

## 4.5 Testing

Proving the overall effectiveness of space radiation protection in a ground test program is not generally practicable because of the inability to simulate the space-radiation environment fully. However, for situations involving shielding materials or large shielding thicknesses for which the available experimental data are inadequate for the design requirements, it is recommended that experiments be performed with accelerators or radioisotopes to obtain sufficient radiation transmission data to verify design calculations. Also, for situations in which a significant part of the necessary radiation protection is provided by such masses as vehicle structure, stores, and equipment, and for which a significant part of the uncertainty results from lack of knowledge about the spatial distribution of these masses, direct measurements of the mass distribution should be made, using a technique such as, for example, a gamma-ray probe (ref. 93). Evaluation of the overall radiation hazard and radiation protection should be included, to the extent practicable, as part of the flight-test program.

# REFERENCES


1. Anon.: Radiation Quantities and Units. ICRU Rept. No. 11, International Commission on Radiological Units and Measurements, 1968.

2. Trubey, D. K.: Use of ICRU-Defined Quantities and Units in Shielding. Rept. ORNL-RSIC-16, Oak Ridge National Lab., Oct. 1968.

3. Langham, W. H., ed.: Radiological Factors in Manned Space Flight. National Academy of Sciences, National Research Council (Washington, D.C.), 1967.

4. Janni, J. F.; and Holly, F. E., eds.: The Current Experimental Approach to the Radiological Problems of Spaceflight. Aerospace Medicine, vol. 40, no. 12, Dec. 1969, pp. 1439-1567.

5. Baker, M. B.: Geomagnetically Trapped Radiation. AIAA J., vol. 3, no. 9, Sept. 1965, pp. 1567-1579.

6. Webber, W. R.: An Evaluation of the Radiation Hazard Due to Solar Particle Events. Rept. D2-90469, The Boeing Co., Dec. 1963.

7. Snyder, J. W.: Radiation Hazard to Man from Solar Proton Events. J. Spacecraft Rockets, vol. 4, no. 6, June 1967, pp. 826-828.

8. Severny, A. B.: On the Behavior of Magnetic Fields Associated with Solar Flares. AAS-NASA Symposium on the Physics of Solar Flares. NASA SP-50, 1964, pp. 95-101.

9. Weddell, J. B.: Association of Flares with Stationary Points of Zero Magnetic Field. AAS-NASA Symposium on the Physics of Solar Flares. NASA SP-50, 1964, pp. 103-106.

10. Modisette, J. L.; Vinson, T. M.; and Hardy, A. C.: Model Solar Proton Environments for Manned Spacecraft Design. NASA TN D-2746, 1965.

11. Yucker, W. R.: Statistical Analysis of Solar Cosmic Ray Proton Dose. Rept. MDC-G0363, McDonnell Douglas Astronautics Co., June 1970.

12. Weddell, J. B.; and Haffner, J. W.: Statistical Evaluation of Proton Radiation from Solar Flares. Rept. SID 66-421, North American Aviation, Inc., July 1966.

13. Hill, C. W.; Ritchie, W. B.; and Simpson, K. M., Jr.: Data Compilation and Evaluation of Space Shielding Problems. Vol. III – Radiation Hazards in Space, Rept. ER 7777, Lockheed-Georgia Co., Apr. 1966.

14. Lahti, G. P.; Karp, I. M.; and Rosenbaum, B. M.: MCFLARE, A Monte Carlo Code to Simulate Solar Flare Events and Estimate Probable Doses Encountered on Interplanetary Missions. NASA TN D-4311, 1968.

15. Roberts, W. T.: Probabilities of Solar Flare Occurrence. NASA TM X-53463, 1968.

16. Webber, W. R.: An Evaluation of Solar Cosmic Ray Events During Solar Minimum. Rept. D2-84274-1, The Boeing Co., June 1966.

17. Masley, A. J.; and Goedeke, A. D.: Solar Cosmic Ray Event Characteristics, Solar Minimum Versus Solar Maximum. Space Research VII, North-Holland Publishing Co. (Amsterdam), 1966, pp. 797-805.

18. Masley, A. J.; and Goedeke, A. D.: Complete Dose Analysis of the November 12, 1960 Solar Cosmic Ray Event. Life Sciences and Space Research, ed. by R. B. Livingston, A. A. Imschenetsky, and G. A. Darbyshire. North-Holland Publishing Co. (Amsterdam), 1963, pp. 95-109.

19. Kane, S. R.; and Winckler, J. R.: The Critical Analysis of Balloon Flights at Minneapolis During the November 1960 Solar Cosmic Ray Flare Events. Technical Rept. CR-124, Univ. of Minnesota, Jan. 1969.

20. Anon.: Magnetic Fields – Earth and Extraterrestrial. NASA Space Vehicle Design Criteria (Environment), NASA SP-8017, 1969.

21. Haffner, J. W.: Calculated Dose Rates in Jupiter's Van Allen Belts. AIAA J., vol. 7, no. 12, Dec. 1969, pp. 2305-2311.

22. King, J. H.: Models of the Trapped Radiation Environment. Vol. IV – Low Energy Protons. NASA SP-3024, 1967.

23. Vette, J. I.; Lucero, A. B.; and Wright, J. A.: Models of the Trapped Radiation Environment. Vol. II – Inner and Outer Zone Electrons. NASA SP-3024, 1966.

24. Vette, J. I.; Lucero, A. B.; and Wright, J. A.: Models of the Trapped Radiation Environment. Vol. III – Electrons at Synchronous Altitudes. NASA SP-3024, 1967.

25. Collected Papers on the Artificial Radiation Belt from the July 9, 1962 Nuclear Detonation. J. Geophys. Res., vol. 68, no. 3, Feb. 1963.

26. Vette, J. I.: Models of the Trapped Radiation Environment. Vol. I – Inner Zone Protons and Electrons. NASA SP-3024, 1966.

27. Lavine, J. P.; and Vette, J. I.: Models of the Trapped Radiation Environment. Vol. V – Inner Belt Protons. NASA SP-3024, 1969.

28. Hess, W. N.: The Radiation Belts and Magnetosphere. Bliesdell Publishing Co. (Waltham, Mass.), 1968.

29. Anon.: Orbital Integration Computer Program for Trapped Radiation. Radiation Shielding Information Center Code Package No. CCC-116/TRECO, Oak Ridge National Lab.

30. Freden, S. C.; and Paulikas, G. A.: Trapped Protons at Low Altitudes in the South Atlantic Magnetic Anomaly. J. Geophys. Res., vol. 69, no. 7, Apr. 1964, pp. 1259-1269.

31. Shaefer, H. J.: The LET Spectrum of Galactic Radiation Exposure in Space and Its Transition in Shield or Tissue. Protection Against Space Radiation, NASA SP-169, 1968, pp. 43-58.

32. Balasubrahmanyan, V. K.; Boldt, E.; and Palmeira, R. A. R.: Solar Modulation of Galactic Cosmic Rays. J. Geophys. Res., vol. 72, no. 1, Jan. 1967, pp. 27-36.

33. Krimigis, S. M.; and Veribatesan, D.: The Radial Gradient of Interplanetary Radiation Measured by Mariners 4 and 5. J. Geophy. Res., vol. 74, no. 16, Aug. 1969, pp. 4129-4145.

34. Haffner, J. W.: Radiation and Shielding in Space. Academic Press (New York), 1967.

35. Meyer, P.: Cosmic Rays in the Galaxy. Annual Review of Astronomy and Astrophysics, Vol. VII, L. Goldberg, ed., Annual Reviews Inc. (Palo Alto, Calif.), 1969, pp. 1-38.

36. Dye, D. L.: Current Status of Space Radiation Effects on Materials and Components. Protection Against Space Radiation, NASA SP-169, 1968, pp. 19-32.

37. Kelton, A. A.: Radiation Guidelines for Manned Space Vehicles – A Review With Recommendations. Rept. SM-47749, Douglas Aircraft Co., July 1965.

38. Billingham, J.: Apollo Dose Limits. Second Symposium on Protection Against Radiation in Space. Edited by A. Reetz, Jr., NASA SP-71, 1965, pp. 139-141.

39. Ballinger, E. R.: Status of Research To Determine Radiological Response Criteria for Space Missions. Protection Against Space Radiation, NASA SP-169, 1968, pp. 33-42.

40. Trubey, D. K., ed.: Proceedings of the Special Sessions on Radiation Transport and Biological Effects. TID-4500, Office of Technical Services, Dept. of Commerce, 1966.

41. Guthrie, M. P.; Alsmiller, R. G., Jr.; and Gurney, J.: Bibliography, Subject Index, and Author Index of the Literature Examined by the Radiation Shielding Information Center – Space and Accelerator Shielding. Revision 1, Rept. ORNL-RSIC-11, Oak Ridge National Lab., Sept. 1967.

42. Anon.: Abstracts of the Literature Examined by the Radiation Shielding Information Center, Space and Accelerator Shielding. Revision 1, Rept. ORNL-RSIC-12, Oak Ridge National Lab., Sept. 1967.

43. Maskewitz, B. F.; Jacobs, V. A.; and Gurney, J.: Bibliography of the Computer Codes Literature Examined by the Radiation Shielding Information Center. Revision 1, Rept. ORNL-RSIC-15, Oak Ridge National Lab., July 1967.

44. Maskewitz, B.: Abstracts of Digital Computer Code Packages Assembled by the Radiation Shielding Information Center. Rept. ORNL-RSIC-13, Oak Ridge National Lab., 1966.

45. Felten, J. E.: Feasibility of Electrostatic Systems for Space Vehicle Radiation Shielding. J. Astronaut. Sci., vol. 11, no. 1, Spring 1964, pp. 16-22.

46. Bernert, R. E.; and Stikley, Z. J. J.: Magnetic Radiation Shielding Using Superconducting Coils. Second Symposium on Protection Against Radiation in Space. NASA SP-71, 1965, pp. 199-209.

47. Levine, S. H.; and Lepper, R.: The Quasi-Hollow Conductor Magnet as a Space Shield Against Electrons. Protection Against Space Radiation, NASA SP-169, 1968, pp. 189-214.

48. Levy, R. H.; and French, F. W.: The Plasma Radiation Shield: Concept and Applications to Space Vehicles. Protection Against Space Radiation, NASA SP-169, 1968, pp. 93-187.

49. Evans, R. D.: The Atomic Nucleus. McGraw-Hill Book Co., Inc., 1955.

50. Anon.: Studies in Penetration of Charged Particles in Matter. Publication 1133, National Academy of Sciences, National Research Council, 1964.

51. Barkar, W. H.; and Berger, M. J.: Tables of Energy Losses and Ranges of Heavy Charged Particles. NASA SP-3013, 1964.

52. Berger, M. J.; and Seltzer, S. M.: Additional Stopping Power and Range Tables for Protons, Mesons, and Electrons. NASA SP-3036, 1966.

53. Scott, W. W.: Estimates of Primary and Secondary Particle Doses Behind Aluminum and Polyethylene Slabs Due to Incident Solar Flare and Van Allen Belt Protons. Rept. ORNL-RSIC-18, Oak Ridge National Lab., July 1967.

54. Yucker, W. R.; and Lilley, J. R.: CHARGE, a Space Radiation Shielding Code. Rept. DAC-62231, McDonnell Douglas Astronautics Co., Apr. 1969.

55. Alsmiller, R. G., Jr.: High Energy Nucleon Transport. Protection Against Space Radiation, NASA SP-169, 1968, pp. 403-428.

56. Scott, W. W.; and Alsmiller, R. G., Jr.: Comparisons of Results Obtained with Several Proton Penetration Codes. Rept. ORNL-RSIC-17, Oak Ridge National Lab., July 1967.

57. Scott, W. W.; and Alsmiller, R. G., Jr.: Comparisons of Results Obtained with Several Proton Penetration Codes – Part II. Rept. ORNL-RSIC-22, Oak Ridge National Lab., June 1968.

58. Alsmiller, R. G., Jr.: High-Energy Nucleon Transport and Space Vehicle Shielding. Nucl. Sci. Eng., vol. 27, no. 2, Feb. 1967, pp. 158-189.

59. Kinney, W. E.: The Nucleon Transport Code (NTC). Rept. ORNL-3610, Oak Ridge National Lab., Aug. 1964.

60. Irving, D. C.; Moran, H. S.; and Kinney, W. E.: Modification and Further Development of the Nucleon Transport Code (NTC). Rept. ORNL-TM-1866, Oak Ridge National Lab., Mar. 1969.

61. Alsmiller, R. J., Jr.; Wachter, J. W.; and Moran, H. S.: Calculation of the Neutron and Proton Spectra From Thick Targets Bombarded by 450 MeV Protons and Comparison with Experiment. Nucl. Sci. and Eng., Vol. 36, no. 3, June 1969, pp. 291-294.

62. Snyder, W. S.; Wright, H. A.; Turner, J. E.; and Neufeld, J.: Calculations of Depth-Dose Curves for High-Energy Neutrons and Protons and Their Interpretation for Radiation Protection. Nuclear Applications, vol. 6, no. 4, Apr. 1969, pp. 336-343.

63. Alsmiller, R. G., Jr.; Irving, D. C.; and Moran, H. S.: The Validity of the Straightahead Approximation in Space Vehicle Shielding Studies. Nucl. Sci. and Eng., vol. 32, no. 1, Apr. 1968. pp. 56-61.

64. Alsmiller, R. G., Jr.; Barish, J.; and Scott, W. W.: The Effects of Multiple Coulomb Scattering and Range Straggling in Shielding Against Solar Flare Protons. Nucl. Sci. Eng., vol. 35, no. 3, Mar. 1969, pp. 405-406.

65. Hill, C. W.; Ritchie, W. B.; and Simpson, K. M., Jr.: Data Compilation and Evaluation of Space Shielding Problems. Vol. IV – LSVDC4 Program System. Rept. ER 7777, Lockheed-Georgia Co., Feb. 1967.

66. Barton, J. A.; Mar, B. W.; et al.: Computer Codes for Space Radiation Environment and Shielding. AFWL-TR-64-71, Air Force Weapons Lab., Aug. 1964.

67. Wallace, R.; Steward, P. G.; and Sondhaus, C. A.: Primary and Secondary Proton Dose Rates in Spheres and Slabs of Tissue. Rept. UCRL-10980, Rev., Univ. of California, Lawrence Radiation Lab., July 1964.

68. Hildebrand, R. I.; and Renkel, H. E.: The Lewis Proton Shielding Code. NASA TM X-52166, 1966.

69. Jordan, T. M.: SIGMA, A Computer Program for Space Radiation Dose Analysis Within Complex Configurations. Rept. DAC-60878, Douglas Aircraft Co., Nov. 1967.

70. Malone, C. F.: Computer Program Users Manual. Vol. I – Program K019 Shield Thickness Calculation Program. NASA Project No. 3066, 1965.

71. Liley, B.; and Schaedle, G. C.: An Examination of the Relative Merits of Stochastic and Nonstochastic Methods of Computing Primary Ionization Doses. Second Symposium on Protection Against Radiation in Space. NASA SP-71, 1965, pp. 527-533.

72. Reetz, A., Jr.; and O'Brien, K.; eds.: Protection Against Space Radiation. NASA SP-169, 1968.

73. Reetz, A., Jr., ed.: Second Symposium on Protection Against Radiation in Space. NASA SP-71, 1965.

74. Anon.: Proceedings of the Symposium on the Protection Against Radiation Hazards in Space. TID-7652, Office of Technical Services, Dept. of Commerce, 1962.

75. Fortney, R. E.: Flight Experiment Shielding Study (FESS) Satellite Data Analysis. Rept. AFWL-TR-68-108, Air Force Weapons Lab., Apr. 1969.

76. Shen, S. P.: Nuclear Problems in Radiation Shielding in Space. Astronautica Acta, vol. 9, 1963, pp. 211-274.

77. Biswas, S.; and Fichtel, C. E.: Composition of Solar Cosmic Rays. Space Science Reviews. Vol. IV, no. 5/6, 1965, pp. 709-736.

78. Berger, M. J.; and Seltzer, S. M.: Tables of Energy Losses and Ranges of Electrons and Positrons. NASA SP-3012, 1964.

79. Berger, M. J.; and Seltzer, S. M. : Penetration of Electrons and Associated Bremsstrahlung Through Aluminum Targets. Protection Against Space Radiation, NASA SP-169, 1968, pp. 285-322.

80. Berger, M. J.; and Seltzer, S. M.: Electron and Photon Transport Programs. NBS 9836 and NBS 9837, National Bureau of Standards, Washington, D.C., June 1968.

81. Jordan, T. M.: BETA – A Monte Carlo Computer Program for Bremsstrahlung and Electron Transport Analysis. AFWL-TR-68-111, Air Force Weapons Lab., Oct. 1968.

82. Mar, B. W.: An Electron Shielding Analysis for Space Vehicles. Nucl. Sci. and Eng., vol. 24, no. 2, Feb. 1966, pp. 193-199.

83. Jupiter, C. P.; Lonergan, J. A.; and Merkel, G.: An Experimental Study of the Transport of Electrons Through Thick Targets. Protection Against Space Radiation, NASA SP-169, 1968, pp. 249-283.

84. Koch, H. W.; and Motz, J. W.: Bremsstrahlung Cross-Section Formulas and Related Data. Rev. Mod. Phys., vol. 31, no. 4, Oct. 1959, pp. 920-955.

85. Dance, W. E.; and Rainwater, W. J.: Investigation of Bremsstrahlung Production in Spacecraft Materials. NASA CR-1377, July 1969.

86. Rester, D. H.; and Dance, W. E.: Electron Bremsstrahlung Cross Section Measurements. Protection Against Space Radiation, NASA SP-169, 1968, pp. 215-247.

87. Burrell, M. O.; and Watts, J. W., Jr.: Plane Isotropic Buildup Factors for Bremsstrahlung Calculations. Protection Against Space Radiation, NASA SP-169, 1968, pp. 517-527.

88. Moshofsky, R. P.: Errors From Geometric Approximations Introduced in Three Computational Models for Space Vehicle Electron Dose Prediction. Edited by A. Reetz, Jr. Second Symposium on Protection Against Radiation in Space, NASA SP-71, 1965, pp. 465-471.

89. Zerby, C. D.; and Keller, F. L.: Electron Transport Theory, Calculations, and Experiments. Nucl. Sci. and Eng., vol. 27, no. 2, Feb. 1967, pp. 190-218.

90. Scott, W. W.: Comparisons of the Results Obtained With Several Electron-Penetration Codes. Rept. ORNL-RSIC-28, Oak Ridge National Lab., Mar. 1970.

91. Billings, M. P.: SWORD, A Computer Program for Space Radiation Shield Optimization in Complex Geometry. Rept. MDC-G0362, McDonnell Douglas Astronautics Co., June 1970.

92. Jordan, T. M.; Koprowski, E. F.; and Langley, R. W.: Shielding Requirements for Manned Orbiting Space Stations. Second Symposium on Protection Against Radiation in Space, edited by A. Reetz, Jr. NASA SP-71, 1965, pp. 415-427.

93. Krumbein, A. D.; Ross, R. C.; and Beaulieu, C.: A Gamma-Ray Probe System for Determining the Shielding Effectiveness of the Apollo Vehicle. Second Symposium on Protection Against Radiation in Space, edited by A. Reetz, Jr. NASA SP-71, 1965, pp. 257-262.

94. Hardy, A. C.; and Snyder, J. W.: Evaluation of Gamma Probe Shielding Verification for the Gemini and Apollo Vehicles. Protection Against Space Radiation, NASA SP-169, 1968, pp. 539-554.

95. Thede, A. L.; and Radke, G. E.: A Correlation of Dosimetric Measurements with Charged Particle Environment of the Inner Van Allen Belt. Protection Against Space Radiation, NASA SP-169, 1968, pp. 75-92.

96. Thede, A. L.: OV3-4 Dose Rate and Proton Spectral Measurements. Rept. AFWL-TR-68-128, Air Force Weapons Lab., Jan. 1969.

97. Schneider, M. F.: Dose and Depth Dose Measurements on the Sixth Gemini Flight, A Comparison with the Gemini-4 Radiation Measurements. Rept. AFWL-TR-68-80, Air Force Weapons Lab., Sep. 1968.

98. Stovall, R. L.; Case, R. S.; Janni, J. F.; and Schneider, M. F.: A Comparison of Measured to Calculated Dose for the Gemini-IV and VI Space Flights and WL-304 Space Probe. Protection Against Space Radiation, NASA SP-169, 1968, pp. 581-610.

99. Warren, C.; and Baker, B.: Radiation Measurements on the Ninth Mercury-Atlas Mission (MA-9). NASA TN D-2608, 1965.

100. Modisette, J. L.; Snyder, J. W.; and Juday, R. D.: Space Radiation Environment. Protection Against Space Radiation, NASA SP-169, 1968, pp. 1-17.

101. Stormer, C.: Polar Aurora. Oxford University Press (London), 1955.

102. Lim, W. C.; Verkatesan, D.; and Van Allen, A. J.: Latitude Survey of Cosmic Ray Intensity by Explorer 7, October 1959 to February 1961. J. Geophys. Res., vol. 68, no. 17, Sept. 1963, pp. 4885-4896.

103. Carosella, C. A.: Shielding of Solar Cells Against Van Allen Belt Protons. J. Spacecraft Rockets, vol. 5, no. 7, July 1968, pp. 878-880.

104. Anon.: Report of the RBE (Radiobiological Effectiveness) Committee to the International Commissions on Radiological Protection and on Radiological Units and Measurements. Health Phys., vol. 9, no. 4, Apr. 1963, pp. 357-384.

105. Jaeger, R. G.; et al., eds.: Engineering Compendium on Radiation Shielding. Vol. I – Shielding Fundamentals and Methods. Springer-Verlag New York, Inc., 1968.

106. Burrell, M. O.: The Calculation of Proton Penetration and Dose Rates. Second Symposium on Protection Against Radiation in Space, edited by A. Reetz, Jr. NASA SP-71, 1965, pp. 493-505.

107. Madey, R.; and Huetter, G. T.: The Attenuation of Space Protons by Thin Cylindrical Shell and Slab Disk Shields. Nucl. Sci. and Eng., vol. 35, no. 3, Mar. 1969, pp. 406-408.

108. Nakache, F. R.: Analytical Formulation of Proton Dose Rates Behind Spherical Multilayer Shields. Second Symposium on Protection Against Radiation in Space, edited by A. Reetz, Jr. NASA SP-71, 1965, pp. 485-491.

109. Burrell, M. O.; Wright, J. J.; and Watts, J. W.: An Analysis of Energetic Space Radiation and Dose Rates. NASA TN D-4404, Feb. 1968.

110. Hill, C. W.; Simpson, K. M., Jr.; and Ritchie, W. B.: Physical and Biological Dose Calculations for Proton and Alpha Fluxes Incident on a Shielded Man Model. Proceedings of the Special Sessions on Radiation Transport and Biological Effects, TID-4500, Office of Technical Services, Dept. of Commerce, Nov. 1966, pp. 67-78.

111. Baker, M. B.: Geomagnetically Trapped Radiation. Rept. SM-47635, Douglas Aircraft Co., Oct. 1964.

112. Burrell, M. O.; Wright, J. J.; and Watts, J. W. Jr.: The Calculation of Electron and Bremsstrahlung Dose Rates. Protection Against Space Radiation, NASA SP-169, 1968, pp. 529-538.

113. Sondhaus, C. A.; and Evans, R. D.: Vol. III – Radiation Dosimetry. Chapter 26 – Dosimetry of Radiation in Space Flight, Academic Press Inc. (New York), 1969, pp. 453-521.

114. Baker, M. B.; Santina, R. E.; and Masley, A. J.: Modeling of Solar Cosmic Ray Events Based on Recent Observations. AIAA J., vol. 7, no. 11, Nov. 1969, pp. 2105-2110.

115. Krumbein, A. D.; Celnik, J.; Nakache, F. R.; and Troubetzkoy, E. S.: Synthesis of Minimum Weight Proton Shields. Rept. UNC-5049, United Nuclear Corp., Feb. 1963.

# NASA SPACE VEHICLE DESIGN CRITERIA
# MONOGRAPHS ISSUED TO DATE

| | | |
|---|---|---|
| SP-8001 | (Structures) | Buffeting During Atmospheric Ascent, May 1964 – Revised November 1970 |
| SP-8002 | (Structures) | Flight-Loads Measurements During Launch and Exit, December 1964 |
| SP-8003 | (Structures) | Flutter, Buzz, and Divergence, July 1964 |
| SP-8004 | (Structures) | Panel Flutter, May 1965 |
| SP-8005 | (Environment) | Solar Electromagnetic Radiation, June 1965 |
| SP-8006 | (Structures) | Local Steady Aerodynamic Loads During Launch and Exit, May 1965 |
| SP-8007 | (Structures) | Buckling of Thin-Walled Circular Cylinders, September 1965 – Revised August 1968 |
| SP-8008 | (Structures) | Prelaunch Ground Wind Loads, November 1965 |
| SP-8009 | (Structures) | Propellant Slosh Loads, August 1968 |
| SP-8010 | (Environment) | Models of Mars Atmosphere (1967), May 1968 |
| SP-8011 | (Environment) | Models of Venus Atmosphere (1968), December 1968 |
| SP-8012 | (Structures) | Natural Vibration Modal Analysis, September 1968 |
| SP-8013 | (Environment) | Meteoroid Environment Model – 1969 [Near Earth to Lunar Surface], March 1969 |
| SP-8014 | (Structures) | Entry Thermal Protection, August 1968 |
| SP-8015 | (Guidance and Control) | Guidance and Navigation for Entry Vehicles, November 1968 |
| SP-8016 | (Guidance and Control) | Effects of Structural Flexibility on Spacecraft Control Systems, April 1969 |
| SP-8017 | (Environment) | Magnetic Fields – Earth and Extraterrestrial, March 1969 |
| SP-8018 | (Guidance and Control) | Spacecraft Magnetic Torques, March 1969 |
| SP-8019 | (Structures) | Buckling of Thin-Walled Truncated Cones, September 1968 |
| SP-8020 | (Environment) | Mars Surface Models [1968], May 1969 |
| SP-8021 | (Environment) | Models of Earth's Atmosphere (120 to 1000 km), May 1969 |
| SP-8022 | (Structures) | Staging Loads, February 1969 |
| SP-8023 | (Environment) | Lunar Surface Models, May 1969 |
| SP-8024 | (Guidance and Control) | Spacecraft Gravitational Torques, May 1969 |
| SP-8025 | (Chemical Propulsion) | Solid Rocket Motor Metal Cases, April 1970 |
| SP-8026 | (Guidance and Control) | Spacecraft Star Trackers, July 1970 |

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| SP-8027 | (Guidance and Control) | Spacecraft Radiation Torques, October 1969 |
| SP-8028 | (Guidance and Control) | Entry Vehicle Control, November 1969 |
| SP-8029 | (Structures) | Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent, May 1969 |
| SP-8030 | (Structures) | Transient Loads From Thrust Excitation, February 1969 |
| SP-8031 | (Structures) | Slosh Suppression, May 1969 |
| SP-8032 | (Structures) | Buckling of Thin-Walled Doubly Curved Shells, August 1969 |
| SP-8033 | (Guidance and Control) | Spacecraft Earth Horizon Sensors, December 1969 |
| SP-8034 | (Guidance and Control) | Spacecraft Mass Expulsion Torques, December 1969 |
| SP-8035 | (Structures) | Wind Loads During Ascent, June 1970 |
| SP-8036 | (Guidance and Control) | Effects of Structural Flexibility on Launch Vehicle Control Systems, February 1970 |
| SP-8037 | (Environment) | Assessment and Control of Spacecraft Magnetic Fields, September 1970 |
| SP-8038 | (Environment) | Meteoroid Environment Model – 1970 (Interplanetary and Planetary), October 1970 |
| SP-8040 | (Structures) | Fracture Control of Metallic Pressure Vessels, May 1970 |
| SP-8042 | (Structures) | Meteoroid Damage Assessment, May 1970 |
| SP-8043 | (Structures) | Design Development Testing, May 1970 |
| SP-8044 | (Structures) | Qualification Testing, May 1970 |
| SP-8046 | (Structures) | Landing Impact Attenuation for Non-Surface-Planing Landers, April 1970 |
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