N63-15987

II

PROBLEMS IN RADIATION SHIELDING FOR SPACE VEHICLES

J. W. Keller, M. O. Burrell, R. D. Shelton, and J. A. Downey, III

Research Projects Division
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

The interest in manned exploration of space has resulted in a rather clear definition of the requirements for propulsion systems. Either the specific impulse must be increased or else very large vehicles must be developed. It is probable that deep space exploration by mankind will be seriously inhibited if the big-booster approach alone is followed, simply because of propellant, cost, structure, manufacture, transportation, and launch. The strong economic motivation to avoid large vehicles has resulted in several efforts to produce propulsion systems with high specific impulse. Perhaps the most direct application is that promoted under the Orion project, which would use the rapid expansion of fission bomb material to provide propulsion. The nuclear heat exchanger rocket, while less direct or dramatic, would use a nuclear fission reactor to heat the propellant which would drive electric thrust units. Because all of these schemes use nuclear fission as an energy source and because all fission of heavy nuclei results in penetrating radiation, all of these systems must have adequate shielding of some kind if man is to be aboard the spacecraft.

Whether or not the propulsion system uses nuclear energy, there is still a radiation problem. It is probable that every magnetic field in space is filled with energy-charged particle radiation of high penetrating power. Since Hess discovered cosmic rays in 1913, man has broadened his knowledge of space radiation to the extent that he can discuss the radiation belt of Jupiter or the solar flare production of high-energy protons. Space explorers will be concerned with great radiation belts upon leaving the Earth, with the background of cosmic radiation that pervades all space, with the violent particle radiation storms associated with solar activity, and with the radiation belts around planets to be visited.

The physics of the radiation problem has been studied most thoroughly in a number of areas. The stopping of charged particle radiation has been of interest since nuclear physics began. By studying the tracks of charged particles in cloud chambers and emulsions, the physicist could determine the products of nuclear reactions and their energies. Many Nobel laureates studied the interaction of charged particles with matter [1, 2].

Later, when massive accelerators were designed to accelerate charged particles, special studies were made [3] to determine methods for protection of laboratory personnel from radiation. In such applications, special efforts were made to minimize the cost of shielding. These studies, however, were not concerned with minimum-weight systems, and often postulated the appropriate location of a mountainside.

Nuclear radiation shielding has been studied extensively in the past 15 years. The weapons effort, the nuclear submarine program [4], and the nuclear powered airplane program [5], in particular, have contributed tremendously to our knowledge concerning the interaction of neutrons and gamma rays with matter. However, because of environmental and system differences, the nuclear radiation problem for submarines, aircraft, nuclear rocket stages, Orion ships, and electrically-propelled spacecraft are all quite different.

Despite the effort expended in the study of radiation, there are several areas in which there is a decided lack of information: how radiation affects humans; the production of secondary radiation by charged particles; the statistics on solar flares; the radiation belts surrounding the bodies in the solar system. Our satellite instrumentation provides only the crudest sort of measurements. The huge accumulation of information concerning radiation is quite valuable, but far from sufficient for the design of space vehicles.

11.1 Radiation from Nuclear Reactors

The utilization of nuclear reactors in space flight is very probable within the next 10 years. Future experience will define more clearly the ultimate role of nuclear power in space. Nuclear reactors will be employed to furnish the primary power for certain types of space vehicles and will also find application as auxiliary power units.

Typically, the fissioning of a single U^{235} nucleus yields approximately 195 Mev of energy. Some 83 per cent of the fission energy is released in the form of kinetic energy of the two primary fission fragments. The fission fragments are heavy, highly ionizing particles, and their kinetic energy is rapidly dissipated within the reactor in the form of heat. The other 17 per cent of the fission energy is accounted for in the neutrons and gamma radiation that are released instantaneously upon fission, and in the betas, gammas, and neutrinos that are emitted during the decay of the radioactive fission fragments. The shield designer is concerned with highly penetrating neutron and gamma radiation, a large percentage of which escapes from the reactor core.

Neutrons normally account for 5 or 6 Mev per fission. The weighted average of the energies of fission neutrons is approximately 2 Mev. Neutrons having energies of 0.01 to 18 Mev are released during the fission process.

Prompt gamma rays provide a total of about 6 Mev per fission. Energies of 0.1 Mev to 10 Mev are represented; the average energy of prompt gamma radiation is about 1 Mev.

Gamma radiation from radioactive fission products provides about 6 Mev per fission. This radiation is released some time after fission occurs. The quantity of radioactive fission products contained in a reactor core increases during operation. Under constant power operation an equilibrium condition will ultimately be attained where radioactive fission products are decaying at the same rate that they are being formed. The energy of gamma radiation emitted from fission products ranges from about 0.2 to 7 Mev, depending on the parent nuclide. The average energy of decay gammas will vary somewhat since the relative percentage of long-lived fission products increases with reactor operation. Generally, the average energy of fission product gamma radiation is roughly 1 Mev.

To evaluate the total radiation energy released by a reactor, it is necessary to know that there are about 3.1×10^{16} fissions per sec per Mw of reactor heat. From the above energy contributions it is apparent that about 5×10^{17} Mev of energy per sec per Mw of reactor energy are released from neutrons, prompt gammas, and fission product gammas. This is equivalent to 75 Btu/sec.

A discussion of nuclear radiation is incomplete without considering the neutron-induced secondary gammas generated in the surrounding media and reactor shields. The secondaries from a highly shielded reactor may be more important than the primary radiation in calculating the dose at the payload. The reason for this is that the capture gammas generated in many shielding and structural materials are characterized by 6 to 10 Mev gamma rays and if the cross section for neutron capture is relatively high (for example, 2.6 barns in iron), a large fraction of the slow neutrons will be converted into high-energy gamma rays. One solution to this problem is to alloy or intermix the shield with boron, which has a very high cross section for neutron absorption (750 barns) but emits only alpha rays and 0.5 Mev gamma rays which are readily stopped. For instance, a 2 per cent alloy of boron in iron will virtually eliminate the capture gammas.

Gamma rays from neutron inelastic collisions are also an important source of secondary radiation, but in most shielding problems are considered to be of less importance than the capture gammas. This assumption is based on the following properties of inelastic collisions by neutrons. Gamma rays from inelastic neutron collisions are usually characterized by 0.5 to 2 Mev gammas, which are attenuated rapidly in dense shields. Another consideration is that the threshold energy for inelastic scattering is usually near or above 1 Mev. Thus, if a neutron has an inelastic collision with a nucleus, there is a good likelihood that the resulting neutron energy will be near the threshold for inelastic scattering and consequently will not undergo another inelastic collision. Also, if a hydrogenous material is used in the shield, most of the neutrons are quickly degraded in energy below the inelastic threshold energy.

The methods used in shielding neutrons and gamma rays are essentially independent of their origin. The dominating principle is reduction of radiation flux and the associated energy by choosing a shield to absorb as much of the energy as feasible and reduce the transmitted flux. For neutrons the ideal shielding material is hydrogen because on a single collision the neutron energy may be theoretically reduced to zero, regardless of initial energy. On the average, a neutron scattered by hydrogen is degraded to approximately one-half its initial energy. However, the scattering of neutrons by hydrogen is always into the forward hemisphere. Hence, if one seeks a material which scatters the neutron flux out of the beam, some other element such as carbon would be better.

For gamma rays, the ideal shielding materials are those which provide a large number of electrons per unit volume, along with a large photoelectric cross section, such as lead. For such elements, the principal mechanism for the energy reduction of the gamma rays between 0.5 Mev and 5 Mev is Compton scattering on electrons. Photoelectric absorption is the principal means of energy absorption below 0.5 Mev, while pair production is the primary mechanism of energy absorption above 5 Mev. In the latter case, a pair of 0.51 Mev gammas results from the annihilation of a positron and an electron, but these are usually neglected in shielding calculations because they are readily absorbed in the typical gamma shield.

It is seen that the materials which are needed for the proper shielding of reactor radiation have conflicting requirements. Thus, hydrogen or light elements, in general, are needed to shield neutrons and lead, or dense materials, are needed to shield gamma rays. How these difficulties are compromised is a large part of the shielding technology and no attempt will be made here to go into the details of the methods. It is apparent that neutrons slowed down by hydrogeneous material will be more readily captured by the heavier elements which are very likely to emit energy secondary gammas. The inelastic scattering of neutrons, however, is minimized by having a hydrogeneous material which reduces the neutron energy below the threshold for inelastic collisions. Since the hydrogen seems to provide more advantages than disadvantages as a neutron shield, the problem of capture gammas is solved by adding an element such as boron to absorb most of the slow neutrons, and consequently minimize the high-energy capture gammas.

Some of the major problems encountered in shielding against nuclear radiation have been discussed here. However, the radiation problems encountered in space are likely to be quite different from those in the Earth's atmosphere. For example, air scattering is a major source of radiation dose at the payload if a nuclear-powered vehicle is operated in the atmosphere. Radiation escaping from a nuclear rocket into space may be completely ignored. Hence, the use of a reactor shadow shield and shields designed to scatter the radiation away from the rocket may play an important role in space shielding.

One of the controlling factors in determining the shielding necessary for nuclear rockets may be the problem of radiation heating of the propellant. Such heating may be of sufficient severity to cause boiling of the propellant (liquid hydrogen) with subsequent propellant loss and cavitation of the pump resulting; or pressurization of the propellant tank to prevent such boiling may result in unduly thick walls.

Theoretical treatment of the propellant heating problem may be broken down into two main problem areas: (1) the accurate determination of the rate of heat deposition in the propellant as a function of position and time, and (2) the proper treatment of the circulation of the heated propellant (due to both natural and forced convection) within the tank during the heating period which will determine the maximum temperature attained. Problem (1) is being attacked using Monte-Carlo statistical techniques, an approach which should be adequate. Problem (2), however, is far from being resolved. Adequate theoretical treatment appears unlikely. The experimental approach is very difficult without performing full-scale experiments.

Recent Monte-Carlo calculations [6] of radiation heat deposition in cylindrical tanks, 30 ft in diameter and 50 ft long, have shown that for incident 2 Mev neutrons and gammas 97 and 65 per cent, respectively, of the total incident energy was absorbed within the full tank. The difference between the above percentages is attributed to the fact that the mean free path of 2 Mev neutrons in liquid hydrogen is about 3 in. while that for 2 Mev gammas is above 5 ft. The rate of energy deposition as a function of depth into liquid hydrogen is illustrated for both neutrons and gammas in Fig. 11.1.

Another important factor in determining heat deposition in the propellant is the consideration of the secondary gamma radiation resulting from neutron capture in the hydrogen (one 2.23 Mev gamma per capture). For

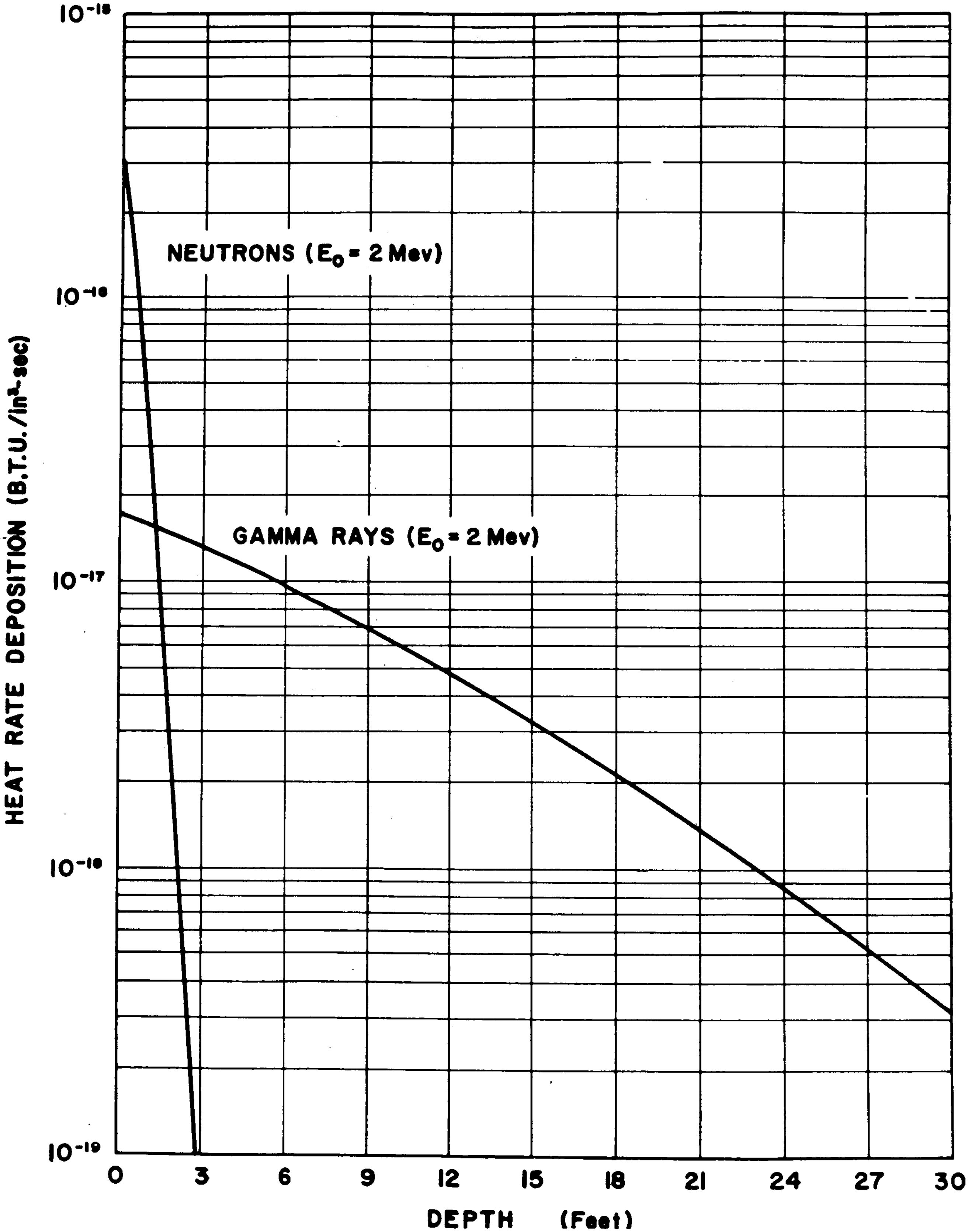

FIG. 11.1 Rate of energy deposition as a function of depth into liquid hydrogen for normally incident neutrons and gamma rays.

this problem the spatial distribution of the neutron captures must be known. Monte-Carlo calculations have been made [6] to determine this distribution as a function of depth in liquid hydrogen for various incident neutron energies. A sample of these results are shown in Fig. 11.2. While these curves give the distribution of neutrons slowed only to 0.5 Mev, they are probably representative of the thermal flux distribution.

It appears that the most satisfactory solution to the propellant heating problem is to shield the reactor sufficiently so that the incident energy will not cause an intolerable temperature rise (within tank pressurization limitations). On the basis of present techniques for determining propellant temperature rise, attempts at system weight optimization are of doubtful value.

Consideration of manned applications for nuclear rockets presents an additional shielding problem. In this case, it is not clear whether the problem of shielding man, or that of shielding the propellant, will be the controlling factor in the design of the reactor shield. If the manned considerations are the controlling factor, then the propellant problem as outlined above is minimized. However, with vehicles becoming larger and larger in diameter, some shielding may be placed so that the outer portions of the propellant tank will be protected from radiation emitted from the sides of the reactor. This shielding would not be effective for protecting the crew.

It is quite impossible to assess fully the shielding problem for manned applications at this time. This is partly because tolerant dose levels for reactor and nautural radiations have not been established for manned missions.

11.2 Natural Radiation in Space

The problem presented by the existence of ionizing radiations in space is a serious one to all proponents of manned space flight. Radiation levels are seen to exist which will be dangerous for an unshielded man; hence, the problem of providing protection with as small a weight penalty as possible. It does not appear that these radiations will have a significant effect on the components of space vehicles, with the exception perhaps of solar cells, which are exposed on outside surfaces.

Since the Van Allen belts are confined to a relatively small region of space which can be rapidly traversed by high-thrust vehicles, they present the limiting problem only for vehicles orbiting in that region, or for low-thrust vehicles spiralling out through the belts. The protons in the inner belt have been found to present a very formidable shielding problem for such vehicles. The electrons in the Van Allen belts, although of high intensity, are relatively easily shielded against because of their low energies. Most of the electrons are stopped in the vehicle shell with only the resulting bremsstrahlung presenting a problem within the vehicle.

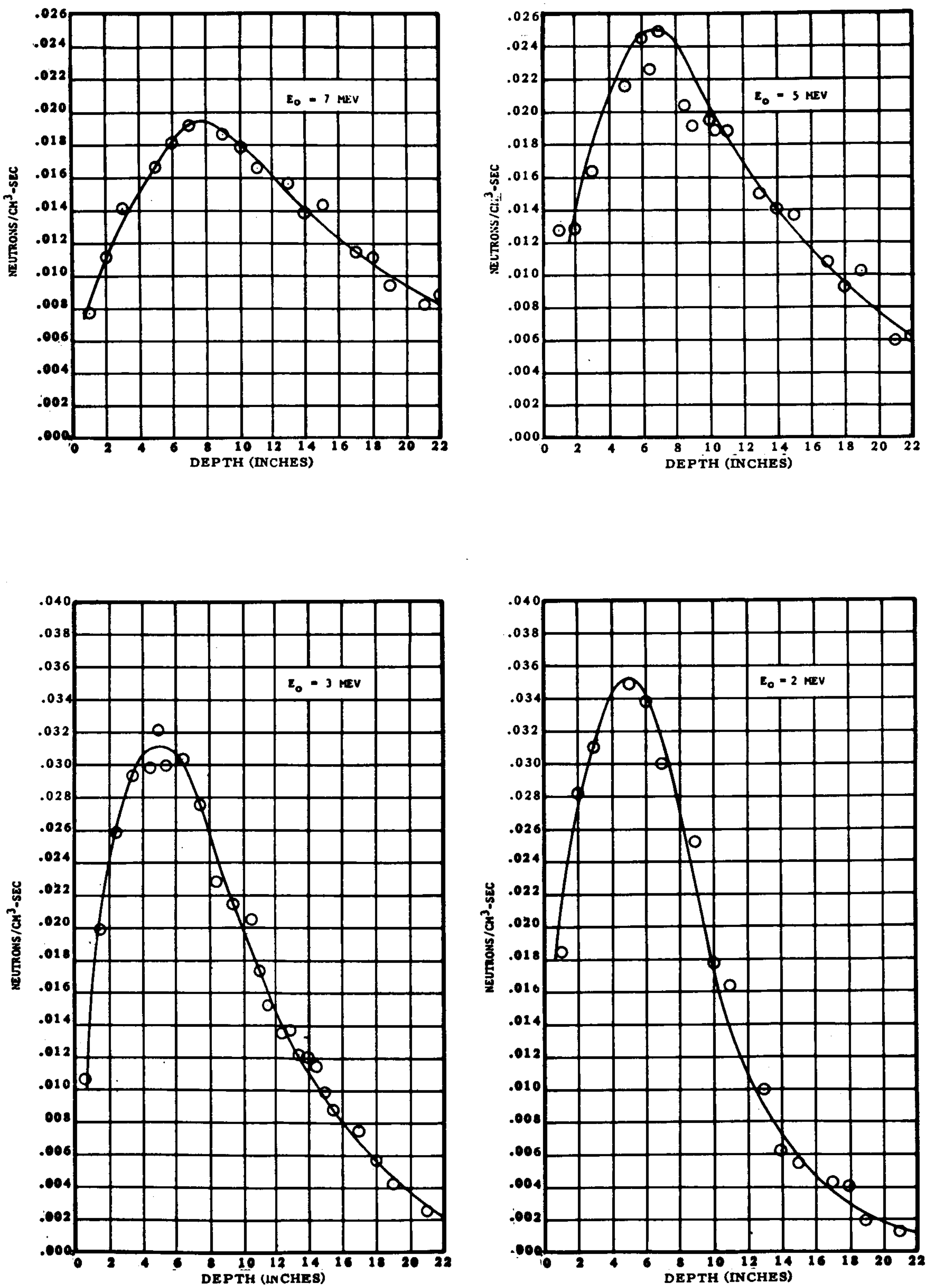

Fig. 11.2 Spatial distribution of 0.5 ev neutrons in liquid hydrogen slabs due to normal-incident monoenergetic neutrons (1 neutron/cm^2 - sec).

For high-thrust vehicles with missions taking them far beyond the Van Allen belts, solar proton outbursts are considered to present the most severe potential hazard from a radiation standpoint. The seriousness of this problem is as yet undecided, primarily because of uncertainties in the time profile for these events. Since the mechanisms for the acceleration and propagation of solar protons are not understood at this time, all considerations of the shielding problem are based upon past observations with no assurance that the worst case possible has been observed. Also, the period of time over which intensive observations have been made represents a rather short sample time upon which to base statistical estimates of encounter probabilities.

All vehicles operating outside the protection of the Earth's magnetic field will be subjected to the full intensity of the background cosmic radiation. It appears that for long missions, on the order of several years, this component may be of significance, with dose estimates of 25 rem/yr having been made [7].

For electrons in the energy range of interest in the Van Allen belts (less than a few Mev) the energy loss in penetration through matter is principally due to electronic excitation and ionization of the atoms in the stopping substance. However, a portion of the energy is lost through radiative collisions (bremsstrahlung). In both types of collisions, the electron may suffer significant deflections in direction. Also, a large number of deflections result from elastic scattering. Consequently, the actual path length of the electron may be considerably greater than the thickness of the absorber being traversed. For electrons, large fractions of the total energy may be transferred in a single collision, resulting in a wide variation in the actual path length for electrons of the same energy. The thickness of shielding needed for stopping the electrons in the Van Allen belts is seen to be quite small with the maximum path length for a 1-Mev electron in aluminum being 0.545 gm/cm^2, a thickness less than that expected for most space vehicle shells.

As the incident electrons are so readily shielded, the only problem within a vehicle would result from the bremsstrahlung radiation produced in the shield. The fraction, f, of the total electron energy, E, which is given up as bremsstrahlung by an electron in the energy range of interest and stopped in a material having atomic number Z may be represented [8] approximately as

$$f \simeq kZE$$

where k is a semi-empirical constant having a value $\sim 7 \times 10^{-4}$ Mev^{-1}. This equation shows that the fraction of the energy lost in this way by Van Allen belt electrons is quite small. However, the large intensity of incident electrons presents a potential hazard. Also, the production of bremsstrahlung is held to a minimum by using a low-Z material for stopping the electrons.

An approximate energy spectrum of the bremsstrahlung is given by [8]

$$N(E_\gamma)d(E_\gamma) \simeq \frac{2\ k\ Z\ (E-E_\gamma)}{E_\gamma}\ d(E_\gamma)$$

where $N(E_\gamma)d(E_\gamma)$ is the number of photons having energies between E_γ and $E_\gamma + dE_\gamma$. It is seen from this equation that the spectrum is quite soft; consequently, a material having a high photoelectric cross section would constitute a very effective shield. The most efficient shield for electrons in the Van Allen belt would be composed of a layer of low-Z material to stop the primary particles followed by a layer of high-Z material to attenuate the bremsstrahlung.

Protons, which constitute the chief shielding problem in space, lose energy mainly through inelastic collisions with bound electrons, causing excitation and ionization. This process results in a practically continuous reduction of energy as the protons penetrate through a medium. As a result of the relative masses of the colliding particles, the protons are not appreciably deflected by such collisions and, therefore, follow essentially straight paths through the material. The maximum energy loss in such a collision is 1/460 of the initial energy so that there is very little variation in the range through a given material for monoenergetic protons (since so many collisions are required to stop the particle). Tabulations of the mean proton range as a function of proton energy for a variety of materials are contained [9].

Plots of the range-energy curves for several materials covering a range of atomic numbers are shown in Fig. 11.3. It is obvious from a comparison on this basis that low-Z materials, hydrogen and hydrogenous materials in particular, are superior because of a greater electron density per unit weight. In actual practice, however, extremely low density materials such as H_2 may not be desirable because of geometric factors.

In shielding against protons in the energy range of interest (up to several Bev), the range of the primary particles is not the only factor which must be taken into consideration. The secondary radiation caused by the interactions of the incident protons with the stopping material must also be considered. The largest dose contribution from secondary radiation originating in the shield should be that due to nucleons emitted as a result of nonelastic collisions with nuclei of the shielding material. Such nonelastic reactions of high-energy nucleons with atomic nuclei are generally thought to take place in two phases. The first phase is the rapid development of a nucleonic cascade; the second is the deexcitation of the thermally excited nucleus by the process of evaporation. The cascade develops through the incident nucleon colliding with nucleons

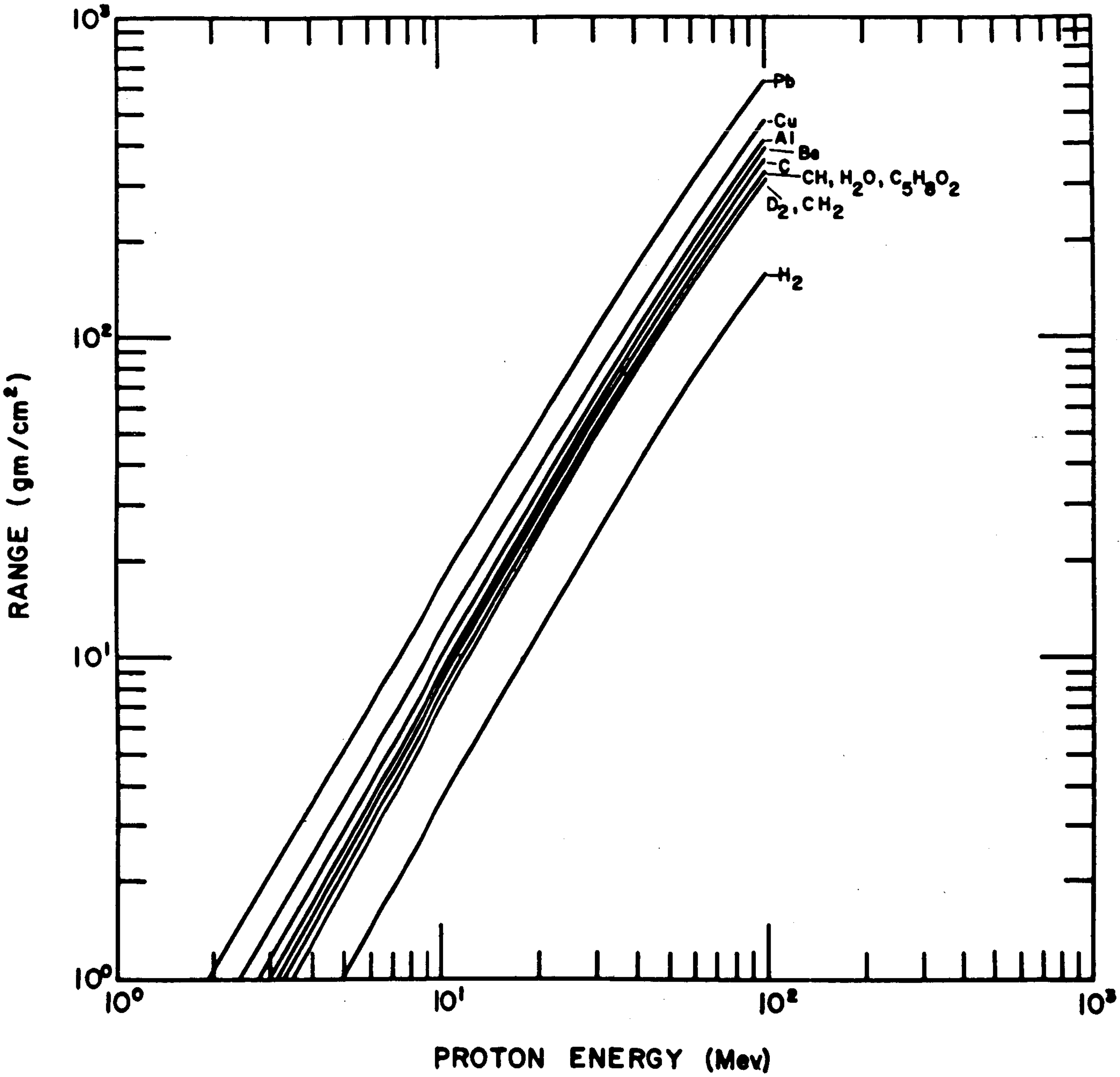

Fig. 11.3 Range-energy curves for protons.

of the target nucleus; the recoil nucleons either escape from the nucleus or collide with other nucleons which, in turn, either escape or collide with still other nucleons. The nucleons that do not escape are assumed to share their energy with the entire residual nucleus from which lower-energy nucleons boil off in the process of deexcitation. The most important particles released by such reactions, from the standpoint of dose behind a shield, should be the neutrons since they do not lose energy by ionization in getting out of the shield as do the released protons.

Considering a beam of protons incident normally on a slab of shielding material, the spectrum of the primary radiation emerging from a thickness, x, may be determined [10] by the equation

$$\phi(E,x)dE = \phi(E';0)\,\frac{S(E')}{S(E)}\,\exp\left[-\int_0^x \Sigma(E_s')\,dS\right] dE$$

where $\phi(E,x)dE$ is the flux of protons between E and E + dE at a distance, x, from the shield surface, S(E) is the stopping power of the shield material for protons of energy E, E' is the incident energy of protons degraded to energy E in traversing a distance x in the shield material, and $\Sigma(E_s')$ is the reaction cross section at a distance s into the shield for protons which entered the shield with energy E'. The calculation of the secondary component of the radiation is much more difficult, since several nucleons may be emitted at various angles and energies following a nonelastic collision, the energy of the cascade particles being high enough to produce tertiary effects in many cases. Also, basic experimental cross section and yield data for such reactions are quite scarce. Most of the estimates of secondaries which have been published have involved the use of extrapolations and interpolations of theoretical determinations of yields from nuclear reactions. Some calculations have assumed straight-ahead production of secondaries [10], while others have considered an angular distribution but have neglected tertiary effects [11]. Proton penetration codes are being formulated based on Monte-Carlo techniques capable of handling these problems more accurately. Also, improved theoretical yield data are being generated for use in these codes. Final application of the codes using the theoretical cross sections will be checked out in a series of accelerator experiments.

Figure 11.4 (taken from [11]) shows estimates of the dose rate as a function of shield thickness at the center of a 4-ft inner radius carbon shield in the most intense portion of the Van Allen proton belt for both the primary protons and the secondary neutrons. In this case, the contribution from tertiary interactions were neglected; however, the relative biological effectiveness (RBE) values used for the neutrons were probably conservative (5 for cascade neutrons and 10 for evaporation neutrons).

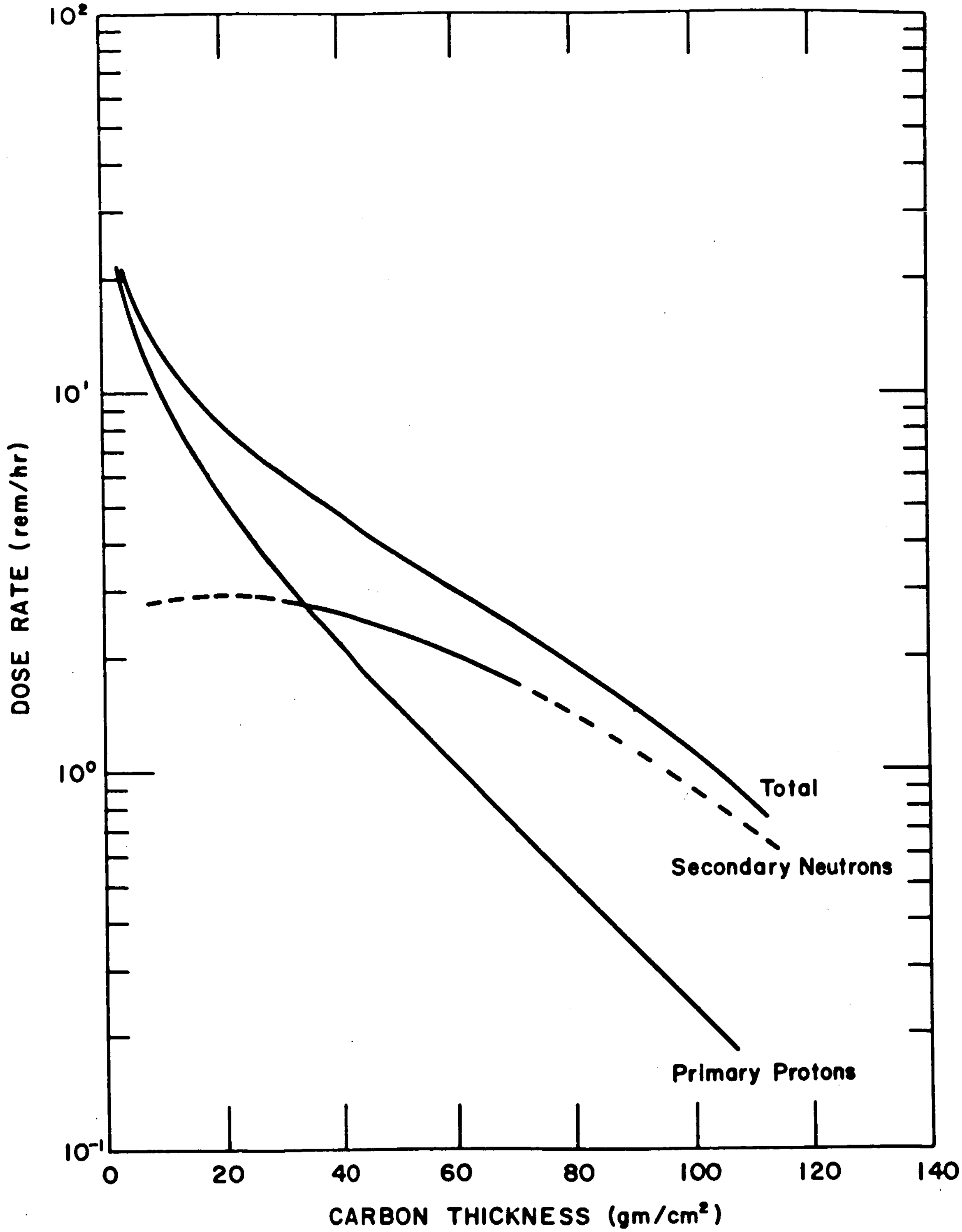

Fig. 11.4 Effect of secondary neutrons on total dose rate for carbon shield (heart of inner van Allen belt).

The cascade neutrons were assumed to have a cosine distribution in the laboratory system while evaporation particles were assumed to be emitted isotropically. The resulting shield thicknesses are seen to be quite formidable with ~100 gm/cm^2 needed to reduce the total dose rate to ~1 r/hr. Consequently, due to the very large shielding penalty involved, the intense regions of the inner Van Allen belt will probably be a forbidden region for manned orbiting vehicles.

Contrary to what might be expected, much of the radiation encountered in solar proton outbursts appears to reach the vicinity of the Earth with an isotropic distribution, thus necessitating protection from all directions. Figure 11.5 (taken from [12]) shows one set of rough upper and lower estimates of the integrated dose as a function of water shield thickness for the low-energy flare events of August 1958, May 1959, July 1959, the intermediate energy event of November 1960, and the high-energy event of February 1956. While the dose is given in rep, the RBE for high-energy protons is close to 1 and, therefore, the units may be considered as rem with little error. However, these curves consider primary radiation alone. Some estimates of the secondary problem for such flares have been made [13].

It is seen that the first few gm/cm^2 of shielding result in a very rapid decrease of the dose, with the addition of subsequent shielding seen to be less and less effective. This is a result of the hardening of the spectrum as more and more material is penetrated. Uncertainties in shield weight increase as thicker shields are used since it requires larger and larger additions of shielding to effect a given percentage change in dose [14].

There are two philosophies which may be applied to the solar flare problem for short duration missions. One is to shield against possible solar flares, the other is to predict flare-free periods during which the mission can be carried out. Satisfactory flare prediction techniques have not been developed as yet and the progress in this area is slow. Consequently, it appears that at least for the early manned flights, shielding may be necessary. For long-duration missions, shielding will undoubtedly be necessary since such long flare-free periods will be rare. Also, the possible hazard from primary cosmic radiation arises.

It is evident that quite heavy shielding will be required in manned space vehicles. Since the addition of such weights will reduce performance, it is important that the shield weight be minimized. Consequently, a number of possible vehicle shielding concepts have been suggested.

One possible means of reducing the shield weight for vehicles operating in the Van Allen region, suggested in [15], takes advantage of the angular distribution of the radiation. It is suggested that, since the radiation is peaked in a direction perpendicular to the lines of force

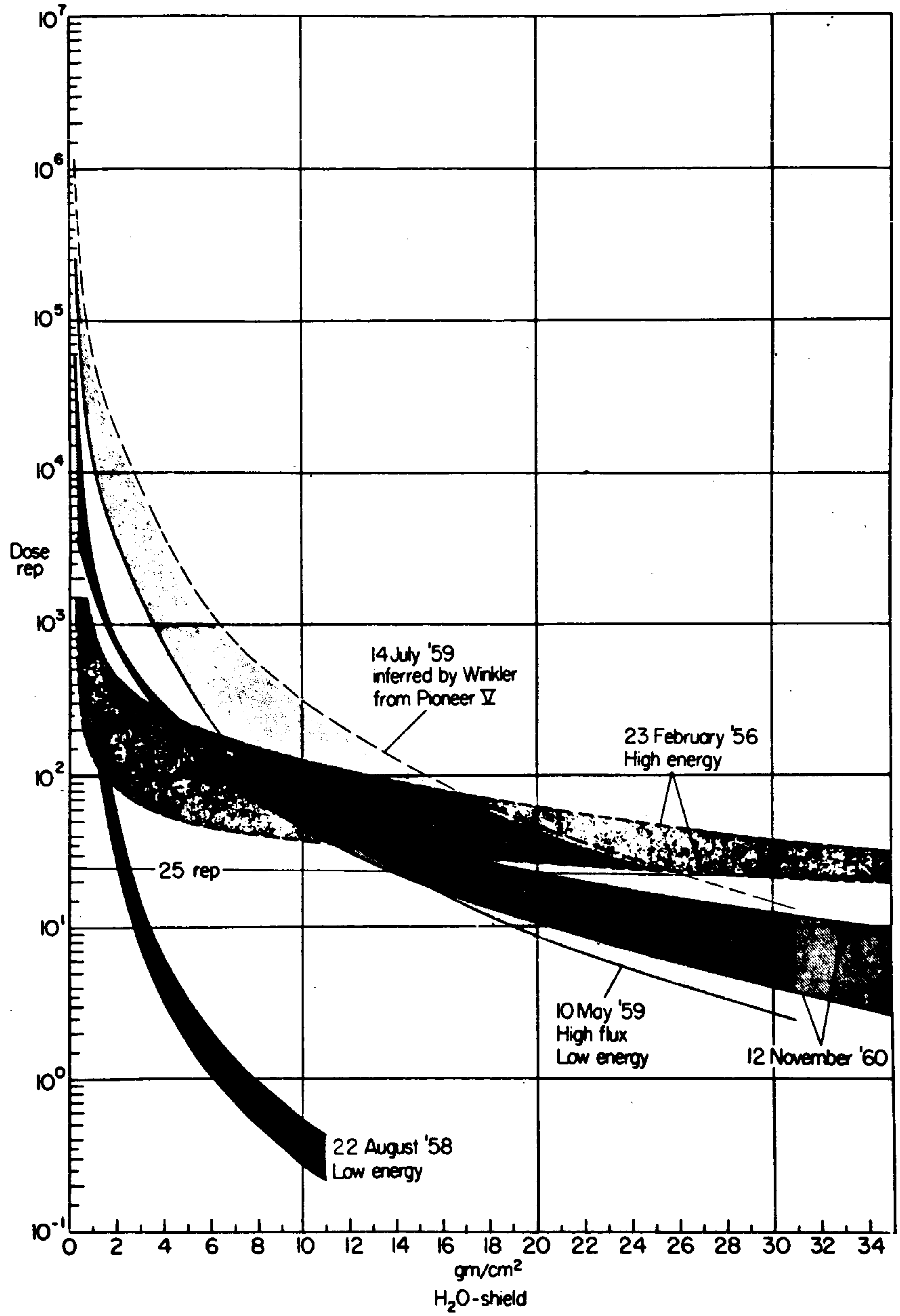

Fig. 11.5 Integrated proton doses versus shield thickness for solar proton events (upper and lower limits).

of the Earth's magnetic field, the crew compartment might be protected by a ring of shielding whose axis is kept parallel to the lines of force at all times. This idea, besides presenting many orientation problems, might not be practical since the angular spread of the radiation may be such that to shield a given volume will require almost the same weight as it would to surround it.

For deep space missions, the fact that one may traverse the Van Allen belts rapidly plus the fact that solar proton outbursts are intermittent in nature, suggests that a possible weight advantage could be realized by using two crew compartments, one large compartment for normal operations during quiet periods and a much smaller heavily shielded compartment for occupation during relatively short periods following large solar flares. The use of a liquid shielding material might allow the shielding to be moved about so as to surround either compartment, making it possible to place a shield of less thickness about the larger compartment. Such an arrangement would reduce the length of stay in the smaller compartment.

An interesting variation [16] of the storm cellar concept would be to place the small heavily shielded compartment between any on-board reactor power source and the large compartment. The shielding surrounding the small compartment would then serve as a reactor shadow shield for the large compartment.

In nuclear as well as nonnuclear vehicles, employment of equipment and stores as shielding could be a means of reducing necessary shield weights. The most obvious application of this concept is the use of propellants as shielding. Such an application should be examined carefully, since fuel depletion would decrease the shielding, perhaps leaving inadequate shielding when needed for a large solar proton outburst. Also, as a result of the low density of such fuels as liquid hydrogen, and the correspondingly large thicknesses of shielding needed for many applications, the shapes assumed by the vehicles utilizing such shielding might not be acceptable aerodynamically for ground launch.

Many persons have suggested the use of active shields such as magnetic fields for protection from the charged particles. Early results of such studies [17] indicate that the scheme is practical only if superconductors are used. Even then, it shows advantages over passive shielding only if very large volumes are to be shielded and a quite high cutoff energy is required. Even in this case, if all the engineering problems such as maintaining cryogenic temperatures are considered, any advantage may disappear. Also, the realiability of such a system is not a problem encountered in the case of bulk shielding. Study in this field, however, is continuing.

One of the most important factors in the shielding problem is the establishment of tolerant dose levels for astronauts. Shield weight will be very strongly dependent upon this parameter since the dose reduction factor obtained with the addition of a given thickness becomes less and less as one shields to lower and lower doses (not to mention geometrical effects). It does not appear unrealistic to assume that the tolerant dose, within limits, may vary from mission to mission depending upon the importance of the mission and the weight available for shielding.

The entire problem area of biological effects of high-energy particles on humans will require much more study before dose limits can be established with confidence.

11.3 Summary

In the exploration of space, many different sources of radiation will be encountered. Of greatest significance will be the energetic protons emitted during certain solar disturbances, the electrons and protons in the Van Allen belts and in radiation belts around other planets, and to a lesser extent the primary galactic cosmic radiation. In addition to the natural radiation environment, on certain missions astronauts will be exposed to neutron and gamma radiation from on-board nuclear reactor sources. Radiation shielding will be required on manned space vehicles, except perhaps during very short flights. The shield designer is confronted with the problem of providing an adequate and structurally sound shield of minimum weight for a particular mission.

The mechanisms of interaction of charged particles (protons and electrons), neutrons, and gamma radiation with matter are quite different. Charged particles ($E \lesssim 1$ Bev) are attenuated primarily through ionization and excitation processes involving bound electrons in the target materials. Low atomic number elements which have a larger number of electrons per unit weight are optimum from a weight standpoint for shielding against charged particles. Low-Z materials also serve as excellent neutron moderators.

A neutron can lose a large percentage of its original energy on a single collision with a nucleus of a light element. In a neutron shield, it is desirable also to include a material such as boron, which has a high absorption cross section for thermal neutrons. It is particularly desirable to reduce the leakage of slow neutrons from a reactor shield to minimize the production of secondary gamma radiation resulting from (n, γ) processes in adjacent materials. A judicious selection of structural materials in a nuclear powered space vehicle can serve to minimize further the production of secondary gammas.

Gamma radiation is attenuated in matter primarily through the processes of photoelectric absorption, Compton scattering, and pair production. The relative importance of these processes on the energy of the incident gamma radiation and on the material through which the radiation is passing. The photoelectric and Compton processes dominate at low energies. The threshold for pair production is 1.02 Mev, and attenuation by pair production becomes increasingly important at higher energies. In general, high atomic number materials are desirable for attenuating gamma radiation.

There will be many different sources of gamma radiation in nuclear-powered space vehicles. Prompt gammas are emitted during the fission process. Gammas are also given off by highly radioactive fission fragments; this radiation necessitates the requirement for reactor shielding after shutdown of a reactor, particularly if the period of operation has been long and there is a large accumulation of fission products. Gamma radiation will be emitted from vehicle components in which radioactivity has been induced by neutron absorption. Gammas will also be formed through nonelastic neutron scattering events. A beam of electrons passing through matter will lose some of its energy through the production of gamma radiation while in the vicinity of a nuclear field - the bremsstrahlung process. Bremsstrahlung radiation may constitute a significant natural radiation hazard for vehicles operating in the outer Van Allen zone (electron belt). It can be seen that there will be numerous potential sources of gamma radiation that must be considered in the shield design of a nuclear powered space vehicle.

Fluxes of known natural space radiation are not sufficiently high to cause damage to space vehicle materials, except for certain radiation sensitive materials exposed on the vehicle's surface, for example, solar cells. On the contrary, nuclear heat-exchanger rockets will operate at very high-power levels, and shielding may be required even on unmanned flights for protection of certain materials and to reduce radiation heating of the propellant.

The design of minimum weight reactor shielding was studied extensively during the nuclear powered aircraft program. However, before the discovery of the Van Allen belts, extensive studies of charged particle shielding were not made except in connection with high-energy accelerator installations where the cost of the shield, not its size or weight, was of primary importance. The ranges of protons and electrons having energies of a few Kev to several hundred Mev can be predicted quite accurately. Thick shields may be required to afford astronauts protection from the energetic protons in space. A certain fraction of the protons entering the shield will encounter high-energy nuclear collisions resulting in the emission of secondary neutrons, protons, and gamma radiation. The yields, direction of emission, and energies of the reaction byproducts can at present only be crudely estimated. These secondary particles will dominate the design of very thick shields, and much more information must be generated on these nuclear collision processes to permit reasonable certainty in the design of shielding for solar flare and Van Allen protons.

Since Van Allen-type radiation is confined to a restricted region in the vicinity of a planetary magnetic field, the solar flare protons will constitute the greatest natural radiation hazard to exploration of the solar system. Satisfactory techniques for the prediction of solar flare events have not been developed. The intensity of radiation, the time profile of the event, and the spectrum of the emitted radiation can vary greatly from flare to flare. There will be serious uncertainties in the design of shielding for space vehicles unless our present knowledge of the natural radiation environment is vastly improved. There is also a dearth of information on the biological effects of radiation, particularly the high-energy protons and secondary neutrons and protons that will be encountered from Van Allen and solar flare radiation. Furthermore, extremely careful and realistic consideration must be given to the establishment of allowable dosages for various classes of missions.

REFERENCES

1. Haliday, D., "Introductory Nuclear Physics," 2nd Edition, Wiley & Sons, Inc., New York, 1955.

2. Bethe, H., Zeitschrift für Physik, 76:293 (1938).

3. Sternheimer, R. M., The Physical Review, 115:137 (1959).

4. Rockwell, III, T., "Reactor Shielding Design Manual," McGraw-Hill Book Co., Inc., New York, 1956.

5. Branch, I. F., Nucleonics, 19:8:27 (1961).

6. Burrell, M. O., Nuclear Radiation Transfer and Heat Deposition Rates in Liquid Hydrogen, MSFC Report (to be published).

7. Tobias, C. A., Radiation Hazards in High Altitude Aviation, Wright Air Development Center Tech. Rep. 52:119 (May 1952)

8. Evans, R. D., "The Atomic Nucleus," McGraw-Hill Book Co., Inc., New York, 1955

9. Rich, M. and R. Madey, Range-Energy Tables, Univ. of Calif. Radiation Lab Rpt. UCRL-2301 (1954).

10. Perkins, J. F., et al, Shielding Problems in Manned Space Vehicles (1st Semi-Annual Report), Lockheed Nuclear Products Rpt. No. NR-104 (July 1960).

11. Keller, J. W., A Study of Shielding Requirements for Manned Space Missions, Convair-Ft. Worth Rpt. FZK-124, (Oct. 1960).

12. Foelsche, T., "Radiation Hazards in Space," a paper presented at Fall Central General Meeting of AIEE, Detroit, Michigan, October 1961.

13. Allen, R. I., et al, Shielding Problems in Manned Space Vehicles (Annual Report, 1960), Lockheed Nuclear Products Rpt. NR-140, (September 1961).

14. Keller, J. W., "Uncertainties in Space Radiation Shielding Calculations," a paper presented at the ARS Space Flight Report to the Nation Meeting, New York (October 1961).

15. Singer, S. F., "Some Consequences of a Theory of the Radiation Belt," a paper presented at the IX IAF Congress, Amsterdam (1958).

16. Keller, J. W. and N. M. Schaeffer, Radiation Shielding for Space Vehicles, Electrical Engineering, 79:1049-1053 (December 1960).

17. Levy, R. H., Radiation Shielding of Space Vehicles by Means of Superconducting Coils, Avco Everett Res. Lab Rpt. 106 (AFBSD-TN-61-7) (April 1961).