trated winds of maximum force surrounding the eye; there winds are almost constant, their speeds frequently exceeding 240 kilometers per hour. In the high-energy core of the storm, wind speeds change but little in the vertical through the first 6100 meters above the ocean; higher, winds usually decrease, change direction, and may become anticyclonic. The decrease in speed and turning of the winds are caused by the warm core and by the tendency for the absolute angular momentum to be conserved at higher levels.

Air flows into the center at low levels, rises near the wall cloud, and then flows outward at some upper level, usually around 12,200 meters in a mature hurricane. The low-level inflow is controlled largely by the frictional forces resulting from the shearing stresses exerted by the winds upon the ocean surface.

The greatest temperature anomalies are found in the upper levels (10,675 to 13,725 meters), where temperatures are frequently 10°C or more above normal. The greatest radial temperature gradients occur in the region extending from the eye outward to the exterior of the wall cloud. The warm core of the hurricane, created along with development of the storm, results from warming of the surface air and the addition of moisture by the oceanic heat source.

Many features of the tropical atmosphere that favor formation of hurricanes such as increased low-level inflow, above-normal warmth in the upper troposphere, and the existence of an anticyclonic circulation at some upper level over a low-level cyclonic disturbance, have been identified. Meteorologists know less, however, about the mechanics of formation of hurricanes than of any other phase of their existence.

The possibilities of controlling hurricanes are intriguing. Project Stormfury, a joint undertaking by ESSA and the U.S. Navy, is designed to explore ways of modifying hurricanes. No fully satisfactory hyopthesis for the control of hurricanes yet exists, and formulation of such a hypothesis may have to await better understanding of the manner in which hurricanes form.

References

1. I. R. Tannehill, *Hurricanes* (Princeton Univ. Press, Princeton, N.J., 1956).
2. G. E. Dunn and B. I. Miller, *Atlantic Hurricanes* (Louisiana State Univ. Press, Baton Rouge, 1964).
3. R. C. Gentry, "The nature and scope of hurricane damage," Hurricane Symp. Amer. Soc. Oceanog., Houston, Texas, October 1966.
4. H. F. Hawkins, *NHRL Rept. 55* (1962).
5. R. C. Gentry, "Structure of the upper troposphere and lower stratosphere in the vicinity of hurricane Isbell, 1964," Tech. Conf. Hurricanes Trop. Meteorol. 4th, Miami Beach, Florida, November 1965; P. Koteswaram "On the structure of hurricanes in the upper troposphere and lower stratosphere," in preparation.
6. H. Riehl, *Tropical Meteorology* (McGraw-Hill, New York and London, 1954).
7. N. E. LaSeur and H. F. Hawkins, *Monthly Weather Rev.* **91**, 694 (1963).
8. J. A. Colon *et al., NHRL Rept. 48* (1961).
9. H. F. Hawkins and D. T. Rubsam, "A study of hurricane Hilda (1964)," in preparation.
10. H. R. Byers, *General Meteorology* (McGraw-Hill, New York and London, 1944).
11. B. I. Miller, *Monthly Weather Rev.* **92**, 389 (1964).
12. ———, *NHRL Rept. 53* (1962).
13. H. Riehl and J. Malkus, *Tellus* **13**, 181 (1961).
14. S. L. Rosenthal, *NHRL Rept. 47* (1961).
15. R. C. Gentry, *NHRL Rept. 69* (1964).
16. J. Malkus, C. Ronne, M. Chaffee, *Woods Hole Oceanog. Inst. Tech. Rept. 8* (1960).
17. H. Riehl, *Science* **141**, 1001 (1963).
18. M. Yanai, "Formation of tropical cyclones," in *Reviews of Geophysics* (Amer. Geophys. Union, 1964), vol. 2(2), pp. 367–414.
19. E. J. Zipser, *NHRL Rept. 67* (1964).
20. NAS, *Weather and Climate Modification, Problems and Prospects,* vol. 2, *Research and Development* (1966).
21. R. H. Simpson *et al., NHRL Rept. 60* (1963); J. S. Malkus and R. H. Simpson, *J. Appl. Meteorol.* **3**, 470 (1964).

The Nucleon-Meson Cascade and Shielding

When a high-energy particle passes through matter, a nucleon-meson cascade develops.

R. G. Alsmiller, Jr.

With the advent of very-high-energy accelerators and manned space flight, shielding against high-energy particles, of energy of the order of 100 million electron volts (1 Mev $= 1.6 \times 10^{-6}$ erg) and greater, has become of increasing significance. While the cost of the shielding is only a small fraction of the cost of a large accelerator, it is high enough so that one cannot afford the luxury of overshielding. Furthermore, the massive shields required for large accelerators often interfere with other desirable design features, and this interference can be kept to a minimum only by careful shield design. In the case of manned space vehicles, weight limitations are very severe, and it is obvious that shielding must be kept to the minimum consistent with adequate protection against radiation.

In both accelerator and spacecraft shielding, the determination of the intensity, energy, and kind of radiation incident on the shield is an important part of the shielding problem, but usually this incident radiation is determined by considerations which cannot easily be influenced. For instance, in the case of accelerators this radiation is determined by such things as the manner of acceleration and the fraction of the beam that strikes the walls of the accelerator during the acceleration cycle, whereas in the case of manned space flight the incident radiation is determined by such considerations as the duration of the flight and the orbit flown.

If the incident radiation is assumed to be known, the shielding problem is to determine the thickness of shield that will reduce this radiation to an acceptable level—that is, to a level which is considered to be not detrimental to a mammalian system. In general, it is not feasible to solve all shielding prob-

The author is a staff member at Oak Ridge National Laboratory, Oak Ridge, Tennessee.

lems by experimental means, and thus theoretical calculations must be employed. Theoretical determination of the shield thickness requires a detailed treatment of the passage of high-energy particles through matter. When a high-energy particle passes through matter, it can interact with a nucleus in the medium and produce a variety of secondary particles. Each of these secondary particles may, in turn, interact with other nuclei to produce additional particles. This general process is usually referred to as a nucleon-meson cascade, and such cascades are the major subject of this article (*1*).

The radiation that is incident on an accelerator shield may be composed of a variety of particles—protons, neutrons, pi mesons, electrons, and so on—depending on the application that is being considered. In general, any of these particles may give rise to a nucleon-meson cascade. In the case of incident high-energy electrons, an electron-photon cascade develops, the cascade photons give rise to photonucleons and photopions, and these particles produce a nucleon-meson cascade. While discussion of an electron-photon cascade and photoproduction is beyond the scope of this article, this nucleon-meson cascade, which is of importance in shielding high-energy electron accelerators, is in principle no different from the cascade induced by other incident particles.

The radiation in space which must be shielded against is composed primarily of protons and electrons. The protons have energies of the order of 1 Gev (1 Gev = 1000 Mev) and below, and are capable of producing a nucleon-meson cascade. The electrons in space, primarily the trapped electrons in the Van Allen belt, are of relatively low energy (less than 10 Mev). Shielding against such low-energy electrons requires physical considerations different from those discussed in this article, and therefore this part of the spacecraft shielding problem is not considered here.

Under many circumstances in both accelerator and spacecraft shielding, the radiation that is incident on the shield may be considered to be composed of protons only, and, for simplicity, consideration here is restricted to this special case. Except for details, most of the discussion can equally well be applied to more general cases.

Interactions in Matter

The development of a nucleon-meson cascade is intimately related to the elementary interactions between the protons, neutrons, and charged pions which make up the cascade and the atoms of the medium in which the cascade is taking place, and thus these interactions must be considered before the cascade itself can be discussed. The term *nucleon* is used when both protons and neutrons are included. Charged pions—that is, charged pi mesons—are particles which have a mass 273 times that of an electron. These pions may be charged either positively or negatively with a charge equal in magnitude to that of an electron. There is a third species of pion which is uncharged, but, since this type of pion is of little significance in the cascade, it is not considered here.

The charged cascade particles, protons and pions, interact with both the atomic electrons and the atomic nuclei of the medium, while the cascade neutrons interact only with the atomic nuclei. In interacting with an atomic electron, the charged particle loses energy and suffers a deflection in its direction of travel, while the atom becomes either excited or ionized. Because of the large mass of the protons and pions relative to the mass of an electron, these particles lose only a small amount of energy and undergo only a small change in direction at each interaction. Consequently, many interactions are required before the particle loses a significant amount of its energy, and, to a good approximation, the loss of energy may be treated as a continuous process. Furthermore, the angular deflections are small and random in direction and so, to a first approximation, may be assumed to cancel one another. Thus, insofar as its interactions with atomic electrons are concerned, a charged cascade particle may be thought of as traveling in a straight line and continuously losing energy.

The energy which a given type of particle loses in traveling a unit distance in a medium is called the stopping power of the medium for this type of particle. For a given type of particle in a given medium, the stopping power is dependent only on the energy of the particle. Over the past several years, much work, both experimental and theoretical, has been done on determining the stopping powers of many media for the cascade charged particles, and these functions are very well known today.

On the basis of the approximation that a particle travels in a straight line and continuously loses energy, the distance that a particle of a given energy will go before coming to rest is fixed and is called the range. The range of a given type of particle in a medium is closely related to the stopping power and can be obtained from the stopping power by integration. The range of protons and charged pions of various energies in a typical material, aluminum, is shown in Table 1 (*2*). Aluminum is a material commonly used in spacecraft. Although it is not often used in accelerator shields, it has roughly the same properties as earth and concrete, which are usually used. The positively and negatively charged pions have the same stopping power and the same range in any material. One should note that the range increases as the particle energy increases, becoming quite large at the higher energies.

A cascade particle's interaction with an atomic nucleus is in general a much more complex physical phenomenon than its interaction with an atomic electron. When a nucleon or pion collides with an atomic nucleus, a nuclear reaction occurs and various particles are emitted. In addition to the neutrons, protons, and charged pions that are emitted from such a collision, many other particles, such as deuterons, alpha particles, and photons, may be emitted. These other particles are, however, emitted at such low energies or in such small numbers that they have little effect on the nucleon-meson cascade and, therefore, are of no interest here.

The number of the various cascade particles that are emitted from a reaction is dependent on the type and energy of the particle that induces the reaction and on the type of nucleus involved. For example, a 400-Mev proton interacting with an aluminum nucleus produces, on the average, 2.7 protons and 1.7 neutrons (*3*). Pions are emitted in appreciable numbers only by nucleons with energies somewhat higher than 400 Mev. In general, the number of particles emitted increases as the energy of the particle that induces the reaction increases. It is the fact that a single particle can, by nuclear reaction, give rise to several particles that makes the phenomenon of a cascade possible.

In addition to knowing the number of particles emitted, it is necessary to know the energy and direction of emission of each particle in order to determine the subsequent interactions of these particles as they pass through matter. Energy is conserved in each reaction, and thus the energy of the incident particle is shared by all the emitted particles. This means, of course, that the emitted particles will have less energy than the particle that induces the reaction. As a result of this lower energy, the emitted particles produce fewer particles when they subsequently interact with nuclei, and thus the cascade particles are prevented from continually increasing in number.

The cascade particles can collide with a nucleus at any point along their path. The average distance they will travel before colliding is called the mean free path for collision and, for energies greater than a few hundred million electron volts, is largely dependent only on the medium being considered. In aluminum this mean free path is approximately 40 centimeters.

At energies of the order of 1 Gev and greater, the range of the charged cascade particles is larger than their collision mean free path, and thus these particles will, on the average, interact with nuclei before they reach the end of their range. At energies of less than about 100 Mev the charged cascade particles will, on the average, slow down and stop before colliding with a nucleus, so their nuclear reactions become unimportant. This is not, however, the case for neutrons, and their interactions with nuclei at the lower energies are very important to the question of shielding. At very low energies (of the order of 10 Mev and less), the neutron-nucleus collisions become predominantly elastic collisions; that is, the neutron no longer induces a nuclear reaction in the nucleus but transfers some of its energy to the nucleus and changes its direction of travel. Thus, at these relatively low energies, no particles other than the recoiling nucleus are emitted but the incident neutron emerges. In each collision, the neutron transfers only a small fraction of its energy to the nucleus, so many collisions are required before the neutron loses essentially all of its energy. Consequently, as we see in the next section, the cascade at very great depths is composed predominantly of low-energy neutrons.

Table 1. Range of protons and charged pions in aluminum.

Energy (Mev)	Range (cm)	
	Protons	Positively and negatively charged pions
26	0.338	1.45
100	3.69	12.8
300	24.2	56.8
500	54.9	102.0
1000	152.0	213.0
5000	1053.0	1007.0
10000	2140.0	1925.0

From what has been stated, it should be clear that a very large amount of information about nuclear reactions is needed for studying the nucleon-meson cascade which develops when a high-energy particle passes through matter. Despite the fact that such reactions have been studied both theoretically and experimentally for many years, the complete information that is needed is not, in general, available. To a large extent the accuracy with which shields, particularly accelerator shields, can be designed is determined by the available information on nuclear reactions.

There is one additional physical phenomenon which is significant in shielding. The charged pions decay into mu mesons (or muons) and neutrinos; that is, the positively charged pion decays into a positively charged muon and a neutrino, and the negatively charged pion decays into a negatively charged muon and a neutrino. Muons are particles which have a mass approximately 207 times that of an electron and may be charged either positively or negatively with a charge whose magnitude is the same as that of an electron. The neutrino is a particle that has neither mass nor charge. The average time that a pion exists before decaying, called the lifetime, is dependent on the pion energy because of relativistic effects. In general, the higher the energy of the pion, the longer its lifetime, and the greater the distance it will travel before decaying. Most higher-energy pions interact with nuclei instead of decaying. Nevertheless, the few very-high-energy pions that do decay are of significance for some shielding purposes.

The neutrino, which is produced when a pion decays, interacts very weakly with matter and therefore is of no interest to us here. It is the properties of the muons that make the pion decays significant in shielding. Muons, because of their charge, interact with atomic electrons but hardly at all with nuclei. Their interaction with electrons may be treated in the same approximation that was used for the charged cascade particles; that is, a stopping power of any medium for muons may be obtained, and from this stopping power the range may be calculated. Furthermore, as with the cascade particles, particularly the pions, the range increases as the energy of the muons increases. The charged cascade particles, however, interact with nuclei, so, when their range becomes much larger than the mean free path for collision, they interact with nuclei and in this manner are prevented from reaching large depths. Since the muons, on the other hand, do not interact with nuclei, once they are formed they travel (unless they decay) to the end of their range, and thus they may reach very great depths if they are formed at sufficiently high energy. The qualification in the statement is introduced because the muons are unstable and decay into electrons or positrons and neutrinos. The lifetime of a muon, however, is very long, and for most shielding purposes this decay may be neglected.

Nucleon-Meson Cascade

Having considered the various interactions that neutrons, protons, pions, and muons undergo in matter, we can now consider the development of the nucleon-meson cascade when a high-energy-proton beam enters matter. For simplicity, it will be assumed that the proton beam is very broad—that is, that the protons are incident over a wide area—so that only the development of the cascade as a function of depth in the matter need be considered. Considerations similar to those given below apply to the case of a very narrow incident beam, but this case is more complicated because the lateral spread of the cascade, as well as its development as a function of depth, must be taken into account.

In discussing the development of the cascade and shielding, it is convenient to distinguish between primary and secondary particles. The term *primary* is used here to denote those incident protons which have not undergone nuclear interaction, while the term *secondary* is used to denote all particles that have been produced by nuclear interaction.

If the incident protons are monoenergetic, the primary protons at any depth are monoenergetic. If the incident protons have a spectrum of energies, the primary protons have a spectrum of energies that changes as a function of depth, because protons of different energies undergo different energy losses per unit distance. At any point along its path a primary proton can collide with a nucleus and give rise to secondary particles. After emission, the secondary cascade particles travel through the medium. If they are charged, they continually lose energy until they collide with a nucleus or come to rest, or decay if they are pions. The neutrons travel through the medium without loss of energy until they collide with a nucleus. At very small depths in the medium—that is, at depths which are much less than a mean free path for collision—most of the incident protons will still be present and few secondary particles will have been formed. At depths of somewhat less than a mean free path, an appreciable number of the primary particles will have interacted and the cascade will be composed of a significant number of both primary and secondary particles. At still greater depths the secondary particles will be enhanced by the nuclear interactions of both the primary particles and the secondary particles produced at small depths. Eventually, of course, the cascade will be composed almost entirely of secondary particles. The depth required for this transition from essentially all primary particles to essentially all secondary particles is, to a large extent, dependent on the energy of the incident protons but is typically of the order of 1 collision mean free path.

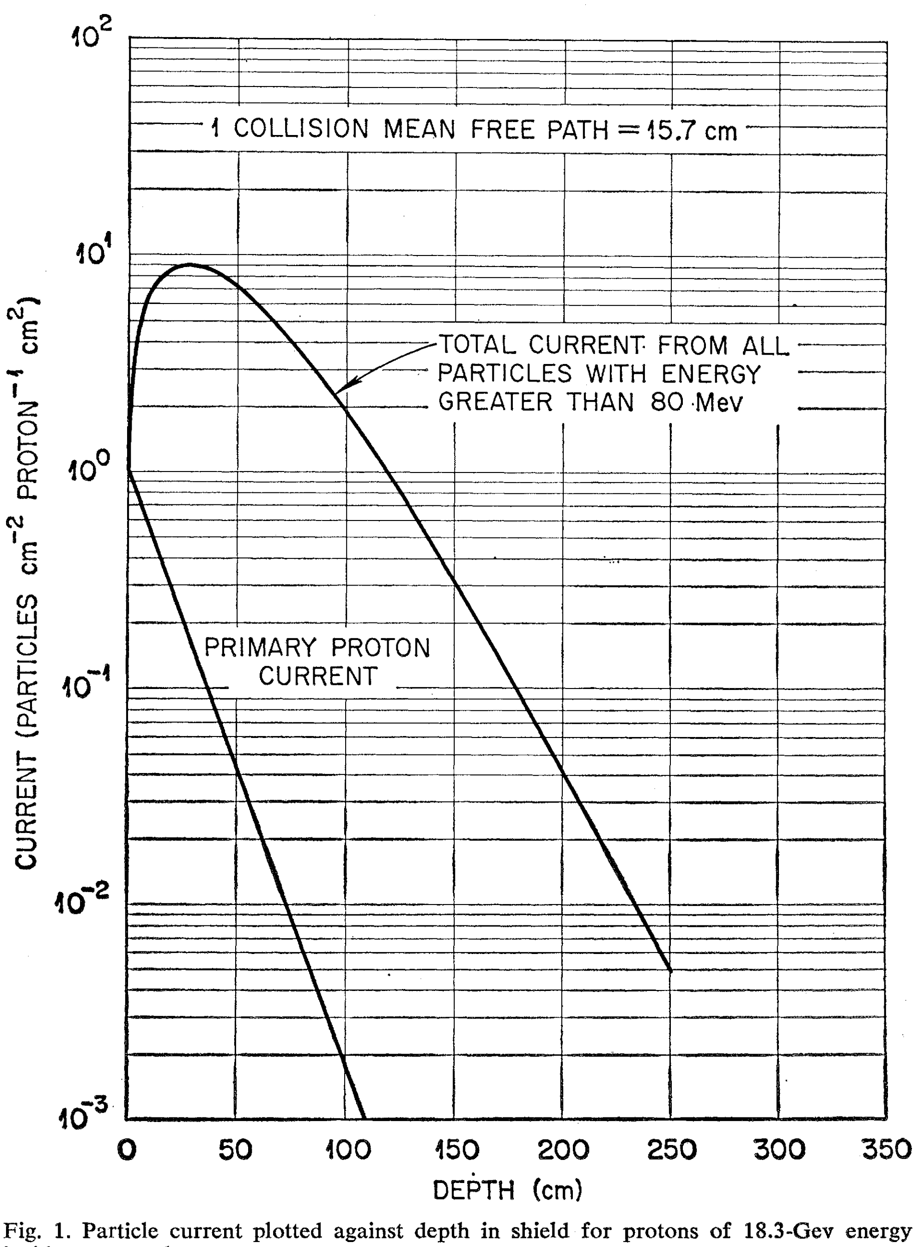

Fig. 1. Particle current plotted against depth in shield for protons of 18.3-Gev energy incident on steel.

The secondary particles do not build up indefinitely with depth because, at each interaction, the energy of the produced particles is lower than that of the incident particle so at each subsequent interaction fewer secondary particles are formed. Also, the secondary charged particles continually lose energy between interactions, and this further reduces the number of particles produced when they interact. In fact, many of the charged secondary particles are produced at such low energies that they come to rest before interacting. The depth at which the number of secondary particles ceases to increase and begins to decrease is dependent on the energy of the incident protons, but is typically of the order of a few collision mean free paths.

This is illustrated in Fig. 1, where the current of all particles—primary protons, secondary protons, neutrons, charged pions, and muons—with energy greater than 80 Mev and the current of primary protons are shown as a function of depth in a steel shield irradiated by protons of 18.3-Gev energy (*4*). These curves were obtained theoretically and must be considered to be very approximate. The particles of energy less than 80 Mev were not considered in the theoretical calculations and are therefore not included in the curves shown. The particle current in this case increases very rapidly at the beginning of the shield and reaches a maximum at a depth of approximately 2 collision mean free paths. At sufficiently great depths the current decreases nearly exponentially with distance. The primary-proton current becomes negligible as compared to the secondary-particle current at a depth of less than a collision mean free path in the case of the incident protons of relatively high energy which are being considered. The maximum value reached by the particle current is, of course, dependent on the energy of the incident protons and will be smaller than that shown in Fig. 1 when incident protons of lower energy are considered.

The numbers of cascade particles of various kinds at a given depth are by no means the same. The continuous energy loss of the charged particles has a very significant influence on both the number and the energy of these particles. This is illustrated in Fig. 2, where the current per unit energy range of secondary neutrons, protons, pions, and muons at two depths in a steel shield irradiated by protons of 18.3-Gev energy is shown (*4, 5*). In Fig. 2, the scale at left pertains to the solid curves; the scale at right, to the dashed curves. The current of positively charged pions was added to the current of negatively charged pions to obtain the curve labeled "pion," and the current of positively charged muons was added to the current of negatively charged muons to obtain the curve labeled "muon." The curves shown refer specifically to the case of a steel shield, but they are representative of cascade results in other materials. At energies of less than a few hundred million electron volts the current per unit energy range is considerably larger for neutrons than for the charged particles. This means that there are many more low-energy neutrons than there are low-energy protons, pions, and muons. The curves shown in Fig. 2 do not extend below 80 Mev because the low-energy particles were not considered in the calculation represented, but physically, of course, the currents extend to very low energies. The difference between the currents per unit energy range for neutrons and for charged particles becomes even more pronounced at energies lower than those shown, because the neutron current continues to increase as the energy decreases, while the charged-particle curves go through a maximum and begin to decrease with decreasing energy. At energies above a few billion electron volts the neutron and charged-particle curves become roughly comparable because, at these energies, the stopping power is small and has only a small effect.

At greater depths the cascade reaches a kind of equilibrium in which the energy dependence of the current per unit energy range for the cascade particles, but not for the muons, changes only very slowly with depth; that is, each of the individual cascade-particle curves shown in Fig. 2 has a shape that is approximately independent of depth. At any given depth the currents per unit energy range of the various cascade particles have markedly different energy dependences, but for a given type of particle this energy dependence is approximately independent of depth. It should be noted that, in this equilibrium region, the currents still decrease with increasing depth, as shown in Fig. 1. The equilibrium merely means that this decrease is approximately independent of the particle energy.

The muon component of the cascade remains to be considered. Since the muons do not produce cascade particles by interacting with nuclei, they do not, once they are formed, contribute to the cascade. They are therefore not important to the development of the cascade, but in some cases they are important to a consideration of shielding. The muons are formed from the decay of the pions throughout the shield. However, since the pions formed in the first few mean free paths of the medium have, on the average, higher energies than those at great depths, muons of relatively high energy are formed predominantly in these first few mean free paths. These high-energy muons, because of their large range, reach very great depths in the medium and tend to be more numerous at great depths than the muons that are produced at great depths. This is, of course, in contrast to the situation for the cascade particles, which travel only a mean free path or so before interacting. The fact that the muons are ultimately lost only when they come to rest has a pronounced effect on the muon current per unit energy range as a function of depth. This is illustrated by the

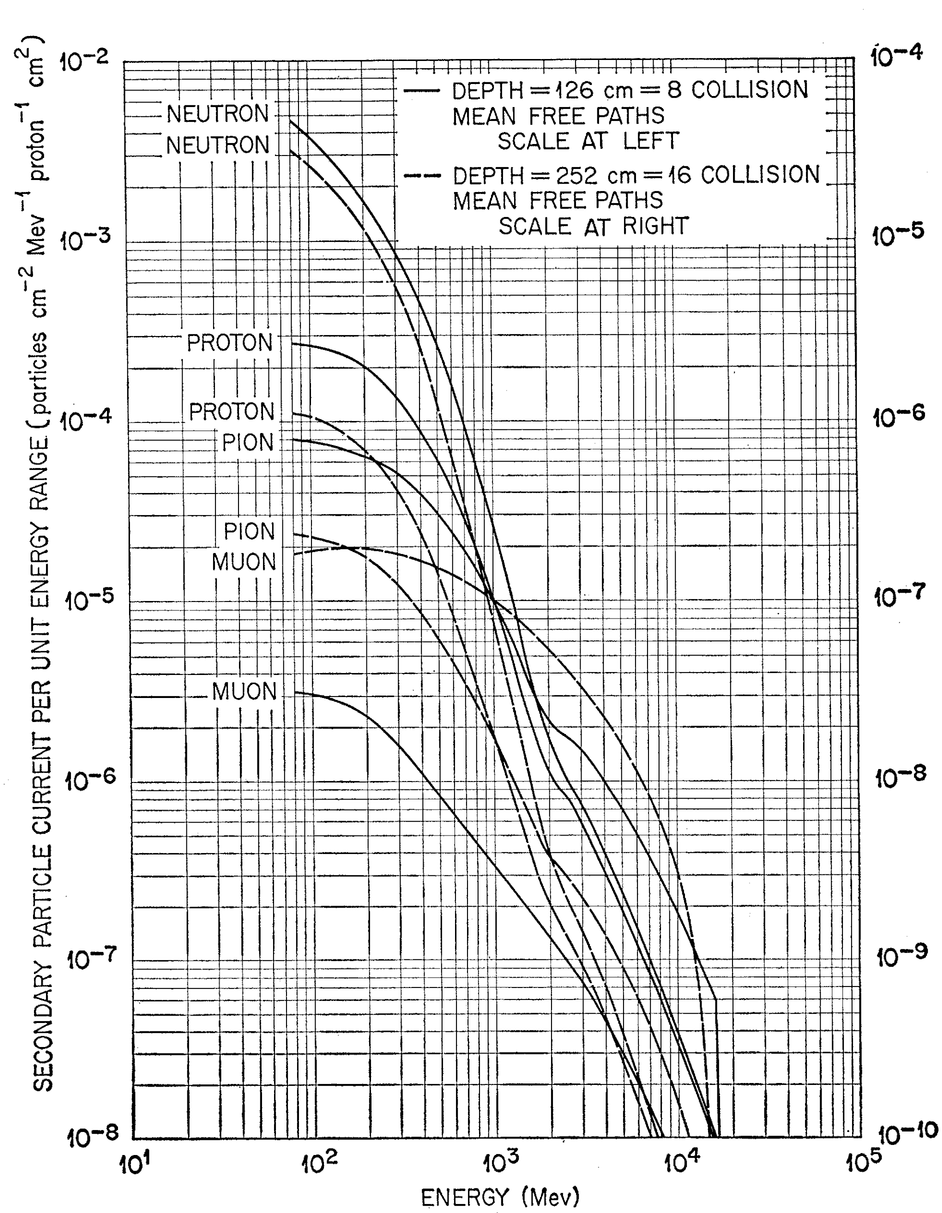

Fig. 2. Secondary-particle current per unit energy range plotted against energy for protons of 18.3-Gev energy incident on steel.

muon current shown in Fig. 2. Between a depth of 126 centimeters (scale at left) and a depth of 252 centimeters (scale at right) the muon current decreases much less than the cascade-particle currents. At a depth of 126 centimeters there are fewer high-energy muons than there are high-energy cascade particles, but at a depth of 252 centimeters this is not the case. At the greatest depth shown in Figs. 1 and 2, the total number of muons is still small enough, as compared to the total number of neutrons, so that the neutrons constitute the major radiation hazard, but the current per unit energy range is decreasing with depth much more rapidly for neutrons than for muons. Thus, at sufficiently great depths the muons will become important.

Dose

Having obtained a measure of the secondary-particle currents per unit energy range emerging from a shield, one needs to obtain from these currents a measure of the radiation hazard associated with them. A discussion of the biological effects of radiation is far beyond the scope of this article. There is, however, a somewhat standard method by which the radiation hazard behind a shield is obtained from the particle currents; I describe this method briefly.

The physical dose may be defined as the energy deposited by charged particles per gram of tissue when the radiation which emerges from a shield impinges on a man. The fundamental assumption is that the energy deposited by the ionization and excitation of the atoms of tissue by charged particles is a measure of the damage to the tissue caused by the radiation. Tissue is a special kind of medium and, in principle, all the interactions discussed in the section on interactions in matter take place in tissue. Therefore, to actually determine the dose which a man will receive from the radiation emerging from a shield, it is necessary to consider the secondary particles produced in the man by nuclear interactions. This is particularly important in the case of the neutrons which emerge from the shield, because, by definition, they contribute to the dose only by producing secondary charged particles. In principle, we might talk of the cascade which develops in the tissue, but this cascade is considerably simplified in the present instance because few high-energy particles emerge from the shield and because a man is sufficiently thin that the cascade does not develop appreciably. Once measures of the charged-particle currents in the man have been obtained, the physical dose can easily be obtained from a knowledge of the stopping power of tissue for the various charged particles. For the real case of a man behind the shield of an accelerator or inside a spacecraft, there are very significant geometric complications. For example, the dose, as it has been defined, will vary at different points in the body and will depend on such things as the orientation of the body with respect to the shield. In practice these geometric complications are ignored and drastic simplifications are used.

The physical dose is obtainable directly from physical consideration and does not depend on biological consideration. A biological dose, which attempts to take into account the fact that some particles are more damaging than others, may also be defined. To obtain the biological dose, one multiplies (i) the energy deposited per gram of tissue by each individual particle by (ii) a quality factor which is dependent on the stopping power of tissue for the particle, and then sums the contributions of all of the particles. The quality factor is a function of the stopping power but is not dependent on the type of particle; that is, different kinds of particles with the same stopping power have the same quality factor. The quality factor is always greater than unity, so the biological dose is numerically greater than the physical dose. In general, the quality factor is large for low-energy particles and small for high-energy particles; consequently, in obtaining the biological dose, the low-energy particles are emphasized. If the quality factor as a function of stopping power is known, the biological dose may, in principle, be calculated from the charged-particle currents in the tissue almost as easily as the physical dose is calculated. There is, however, a very important proviso. As was previously pointed out, when a nuclear reaction occurs, various low-energy particles, alpha particles, recoiling nuclei, and so on are emitted. These particles have little influence on the cascade and were not considered extensively above. Also, because of their low energy, they do not contribute appreciably to the physical dose. They do, however, because of the large quality factor associated with low-energy particles, contribute appreciably to the biological dose. Thus, considerably more information about nuclear reactions is needed to obtain the biological dose than is needed to obtain the physical dose.

Once the dose is calculated, the adequacy of a shield is determined by comparison of this dose with the maximum permissible dose consistent with safety. The quality factor as a function of stopping power and the maximum permissible dose must be determined from biological experiments. These experiments are very complicated and do not by any means yield unambiguous answers. For accelerator-shield design the quality factor and dose limits recommended by the National Committee on Radiation Protection (*6*) and by the International Commission on Radiological Protection (*7*) are usually used. The allowed dose for manned spacecraft is specified by the National Aeronautics and Space Administration and is of necessity different from that for accelerators, since the radiation hazard must be considered in conjunction with the many other hazards of space travel.

Shielding of Manned Space Vehicles and High-Energy Accelerators

There are two sources of protons in space, solar cosmic rays and trapped protons in the earth's magnetic field, which are sufficiently intense to pose a radiation hazard for manned space travel. The familiar galactic cosmic rays are also present in space, but their intensity is sufficiently low that they will not constitute a hazard unless very long missions, of the order of a year or more, are undertaken.

Solar cosmic rays are energetic protons which are emitted when a solar-flare event—a disturbance of poorly understood origin—takes place on the surface of the sun. These particles present the major radiation hazard for space travel outside the earth's magnetic field. Solar-flare events are intermittent, and both the energies and the intensities of the protons associated with different events vary over wide limits. Determination of the radiation that will be incident on the spacecraft during a particular mission is, therefore, very difficult.

The protons that are trapped in the earth's magnetic field are always present but are localized in space. The radiation that is incident on a spacecraft during a given mission is determined by the amount of time the spacecraft spends in the magnetic field—or, more precisely, by the orbit which is flown, since the energies and intensities of the protons vary with position in the magnetic field.

From the point of view of shielding, the most significant feature of both the solar protons and the trapped protons is the fact that they have intensities and energies requiring, at least for missions contemplated in the near future, shield thickness of much less than 1 collision mean free path—a relatively thin shield. This means that the cascade does not develop appreciably either in the shield or in the man behind the shield, and thus is composed predominantly of primary particles. A large fraction of the dose that a man will receive in a typical spacecraft is due to the primary particles, and only a small fraction is due to the secondary particles. This is important because the uncertainty in calculating the dose from secondary particles is much larger than the uncertainty in calculating the dose from primary particles. Thus, for the case of spacecraft in which weight is a very important factor, relatively accurate calculations can be made.

In contrast to the shielding of spacecraft, the incident-particle energies of interest in accelerator shielding may extend into the multi-billion-electron-volt region, depending on the energy of the accelerator being considered. In general, whether we are dealing with an accelerator of modest energy of a few hundred million electron volts or with one of energy in the multi-billion-electron-volt region, the shield thickness required is such that the nucleon-meson cascade goes through its complete development and is well into the equilibrium region before the end of the shield is reached. Consequently, adequate design of an accelerator shield requires a very extensive treatment of the cascade.

Summary

The designing of radiation shields for manned space vehicles and for high-energy accelerators requires a knowledge of the nucleon-meson cascade that develops when a high-energy particle enters matter. The accuracy with which calculations of the nucleon-meson cascade can be made is to a large extent determined by the available information on particle production from nuclear reactions. The accuracy with which an effective shield can be designed is also determined by the available information on the biological effects of radiation.

In the case of present manned space vehicles and those contemplated in the near future, the secondary particles from nuclear reactions contribute only a fraction of the total radiation hazard, and relatively accurate design calculations for radiation shields can be made. In the case of high-energy accelerators, the secondary particles from nuclear reactions contribute the entire radiation hazard, and only very approximate design calculations for shields are at present possible.

References and Notes

1. For a more detailed discussion, see the following publications and references cited therein: S. P. Shen, *Astronaut. Acta* **9**, 211 (1963); R. G. Alsmiller, Jr., in "Proceedings USAEC First Symposium on Accelerator Radiation Dosimetry and Experience, 1965" *Brookhaven Nat. Lab. Pub. CONF-651109 (TID-4500)*, p. 327; ———, *Nucl. Sci. Eng.* **27**, 158 (1967).
2. W. H. Barkas and M. J. Berger, "Tables of Energy Losses and Ranges of Heavy Charged Particles," *Nat. Aeron. Space Admin. Pub. NASA SP 3013* (1964); R. M. Sternheimer, *Phys. Rev.* **115**, 137 (1959).
3. H. W. Bertini, *Nucl. Phys.* **87**, 138 (1966).
4. R. G. Alsmiller, Jr., and J. Barish, *Nucl. Instr. Methods* **36**, 309 (1965).
5. R. G. Alsmiller, in "Proceedings USAEC First Symposium on Accelerator Radiation Dosimetry and Experience, 1965" *Brookhaven Nat. Lab. Pub. CONF-651109 (TID-4500)*, p. 327.
6. "Permissible Dose from External Sources of Ionization Radiation," *Nat. Bur. Std. (U.S.) Handbook 59* (1954).
7. "Report of the RBE Committee to the International Commission on Radiological Protection and on Radiological Units and Measurements," *Health Phys.* **9**, 357 (1963).

8. The research reported here was partially sponsored by the National Aeronautics and Space Administration [order R-104(1)], under Union Carbide Corporation's contract with the U.S. Atomic Energy Commission.

Agrobiology: Specialization or Systems Analysis?

The world-wide phenomenon of accelerated pace in growth and change suggests a new look at problem solving.

Neal F. Jensen

In the United States today, there is an increasing public awareness of the problems associated with world population growth. One of the problem areas directly involves agriculture; clearly it is the role of agriculture to provide the basics for food and clothing. The near disappearance of certain of our national food reserves (previously known as *farm surpluses*) in massive aid infusions to India and other less fortunate countries has sharpened the focus on the relationship between population and food supply.

John Platt (*1*) and Max Ways (*2*) recently have called attention to the exponential nature of change endemic in the world today. In this paper I raise the issue of whether the approach of agricultural scientists to research directed toward most problems of the future is consonant with the accelerated pace of growth and change. The question is: can research remain arithmetical and confined to the present when all else is geometrical and directed toward the future?

The development of hybrid corn by geneticists and plant breeders stands as perhaps the best-known success story attributable to agricultural science, but it is generally forgotten that about 40 years elapsed from the time when the first critical papers were published until hybrid corn began to "move" as a commercial product. Some say this span was necessary to absorb and inte-

The author is professor of plant breeding at the New York State College of Agriculture, Cornell University, Ithaca, New York.