NUCLEON-MESON TRANSPORT CALCULATIONS*

R. G. Alsmiller, Jr.
Neutron Physics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee, 37830

Abstract

A review of medium- and high-energy nucleon-meson transport calculations carried out at the Oak Ridge National Laboratory in the past several years is presented.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

*This research was funded by the U. S. Energy Research and Development Administration under contract with the Union Carbide Corporation.

WASTE

Acknowledgment

Many people have been involved in developing the code HETC and the capabilities which are used in carrying out calculations such as those discussed here. Thanks are due particularly to T. W. Armstrong, J. Barish, H. W. Bertini, K. C. Chandler, T. A. Gabriel, and R. T. Santoro.

I. INTRODUCTION

For a variety of applications - for example, the study of the shielding required for radiation protection in the vicinity of medium- and high-energy accelerators, the design of instrumentation for measuring the energy of high-energy particles, the study of the induced activity in the moon from solar and galactic cosmic-ray bombardment, and the study of the applicability of various particles in cancer radiotherapy - it is desirable to have available calculational methods for studying the transport of medium- and high-energy nucleons and pions through matter. The equations which describe the transport of these particles and the nuclear-reaction products produced by these particles through matter are well established, but the problem of obtaining accurate numerical solutions to the equations for specific conditions is quite formidable. Also, the basic differential particle-production cross-section data that enter into the equations are not available experimentally, and, thus, nucleon- and pion-transport calculations must be based, for the most part, on cross-section data derived from theoretical considerations. For several years, a group at the Oak Ridge National Laboratory have been engaged in developing nuclear cross-section data and techniques for carrying out medium- and high-energy transport calculations, and in this paper some of the results which have been obtained are reviewed.

II. HETC - HIGH-ENERGY TRANSPORT CODE

HETC^{1*} is a transport code developed at ORNL that utilizes Monte Carlo techniques to simulate the nucleon-meson cascade that occurs when high-energy nucleons or pions pass through matter. A detailed discussion of the physical processes included in this code is beyond the scope of this paper, but such a discussion is available.^{3,4} Here, only a few of the more significant aspects of the code will be discussed.

HETC is operable for incident neutrons, protons, charged pions, and muons at all energies less than or of the order of several hundred GeV and for essentially arbitrary material compositions and source-geometry configurations. The code takes into account charged-particle energy loss due to atomic ionization and excitation, multiple Coulomb scattering of incident charged particles, elastic and nonelastic neutron-nucleus collisions, nonelastic collisions of protons and charged pions with nuclei other than hydrogen, elastic and nonelastic collisions of nucleons and charged pions with hydrogen, pion and muon decay in flight and at rest, and particle production from negatively charged pion capture at rest. At energies ≤ 15 MeV, neutron transport in HETC is usually carried out with the Monte Carlo transport code O5R⁵ using a combination of experimental^{6,7} and theoretical cross-section data.⁸ For some purposes, however, it is more convenient to transport the low-energy neutrons by the method of discrete ordinates, and this may also be done.⁹ At energies ≥ 15 MeV, nucleon-hydrogen and pion-hydrogen

*HETC is a high-energy version of an earlier code designated NMTC.² For incident nucleon and pion energies ≤ 3 GeV, there is no significant difference between HETC and NMTC. HETC and an instruction manual for operating the code are available from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.

collisions are treated using basically experimental data,¹⁰⁻¹³ and neutron-nucleus elastic collisions are treated using experimental data and optical-model calculations (e.g., see Refs. 14 and 15 and the many references given therein).

For both nucleons and pions, there is little information on particle production from nonelastic nuclear collisions with nuclei heavier than hydrogen, and thus this information must be obtained theoretically. In HETC, nucleon-nucleus nonelastic collisions in the energy range of 15 MeV to 3.5 GeV and pion-nucleus nonelastic collisions at energies < 2.5 GeV, including negatively charged pion capture at rest, are treated by means of the intranuclear-cascade-evaporation model of nuclear reactions as implemented by Bertini *et al.* in the code MECC-7.^{16*} A detailed discussion of this model and comparisons between calculated results and a variety of experimental data will be found in Refs. 11 and 17-21. This model was intended to describe nonelastic nuclear collisions at energies ≥ 50 MeV, but because of the lack of any other source of data, it is used in HETC at lower energies despite the fact that its use at these lower energies is dubious. Comparisons between calculated and experimental data at these lower energies are given in Refs. 22-25. In particular, the case of particle production from negatively charged pion capture at rest, which is of importance in the study of the applicability of negatively charged pions in radiotherapy, is considered in some detail in the work of Guthrie *et al.*²⁶ A unique feature of HETC is that it contains the code MECC-7 as a subroutine and thus uses the code itself rather than data from the code to

*Except for improved nucleon-nucleon and pion-nucleon cross-section data at the higher energies (> 350 MeV), MECC-7 is the same as MECC-3¹⁶ and is a medium-energy extension of an earlier code designated LECC.

determine the collision products when a nonelastic collision occurs. This use of MECC-7 as a subroutine substantially reduces the data-handling problems in HETC, but it also makes the core requirements for HETC very large since MECC-7 is not a small code.

The intranuclear-cascade-evaporation model as programmed in MECC-7, and therefore in HETC, becomes invalid at nucleon energies ~ 3.5 GeV and pion energies ~ 2.5 GeV because the model accounts for only double-pion production from nucleon-nucleon collisions and for only single-pion production from pion-nucleon collisions. At nucleon energies > 3.5 GeV and pion energies > 2.5 GeV, particle-production data for nonelastic collisions are obtained in HETC from a very approximate extrapolation model due to Gabriel *et al.*²⁷ and to Gabriel and Santoro.²⁸ A detailed discussion of this extrapolation model, as well as a large number of comparisons between calculated and experimental data, will be found in Ref. 27 and in Appendix A of Ref. 28. Basically, the model employs particle-production data obtained from the intranuclear-cascade-evaporation model at energies ~ 3 GeV and uses energy- and angle-scaling relations to estimate particle-production data for higher energy nucleon-nucleus and pion-nucleus collisions. In HETC the intranuclear-cascade-evaporation data, needed for scaling, are generated by the code MECC-7 at each nonelastic collision, and, therefore, as in the intermediate energy range, it is not necessary to store large quantities of data which describe particle production from high-energy nucleon-nucleus and pion-nucleus collisions. The extrapolation model is at best very approximate, but it does provide a detailed description of each high-energy collision; e.g., it gives the mass, charge, and energy of the residual nucleus from the collision, and for this reason it is very suitable for use in transport calculations.

In HETC, all particles in the cascade, i.e., neutrons, protons, π^+ , π^- , μ^+ , and μ^- , are followed until they eventually disappear by escaping from the geometric boundaries of the system, undergo nuclear absorption, come to rest, or, in the case of pions and muons, decay. Electrons and positrons from muon decay and photons from π^0 decay and nonelastic nuclear collisions are not transported by HETC, but information concerning these particles is provided by the code, so that they may be transported with other codes if this is an essential part of the problem. (In the case of photons from nonelastic nuclear collisions, the code gives the total energy emitted from the collision in the form of photons but not the photon spectrum.) HETC also provides the mass number, charge, and location of all of the residual nuclei produced by nonelastic collisions. This information allows a determination of the induced activity in the transport medium as a result of the cascade and, for this reason, is of interest in assessing the radiation hazard in the vicinity of accelerators and in studies of the effects of cosmic-ray bombardment. Finally, HETC provides the energy distribution of all of the residual nuclei produced by nuclear collision and the energy distribution of the low-energy heavy particles, i.e., deuterons, tritons, ^3He 's, and alpha particles, produced by nuclear reactions. These energy distributions are very important in calculating the dose equivalent for radiation-protection purposes and in calculating quantities of biomedical interest such as cell-survival probabilities. In the next section of this paper, examples of these various types of calculations are presented.

III. CALCULATED RESULTS AND COMPARISONS WITH EXPERIMENTAL DATA

In this section, calculated results pertaining to a variety of applications are presented and discussed. For the most part, the applications considered here are those for which experimental data are available, since the validity of the calculated results can be determined only by comparison with such data. The value of such calculations, however, is not only that they may be used to understand existing experimental data, but also that they provide results which are not available and cannot easily be obtained experimentally. All of the calculated results presented in this section, unless otherwise noted, were obtained with the code HETC described in the previous section.

A. Neutron Flux Spectra Induced in the Earth's Atmosphere by Galactic Cosmic Rays⁹

The galactic cosmic-ray proton spectrum contains very high energy protons, and, therefore, the nucleon-meson cascade induced in matter by galactic cosmic rays is of considerable interest for testing the validity of high-energy transport calculations. Furthermore, the neutron flux per unit energy induced in the earth's atmosphere by galactic cosmic rays is of interest for a variety of reasons: e.g., one theory of the origin of the Van Allen proton belt is based on the existence of this neutron flux at the top of the atmosphere,²⁹ and, therefore, experimental data are available on this neutron flux per unit energy as a function of both neutron energy and depth in the atmosphere.³⁰⁻³⁶

Armstrong *et al.*⁹ have compared calculated results, obtained with both incident protons and incident alpha particles, with the available experimental data. The calculations for incident alpha particles were carried

out using a modified version of HETC, which employs an approximate model due to Gabriel *et al.*,³⁷ to describe particle production from high-energy nonelastic alpha-particle-nucleus collisions. In the calculations, the low-energy (< 12 MeV) neutrons were transported with the discrete ordinates code ANISN³⁸ rather than with the Monte Carlo code O5R⁵ usually used in HETC in order that the energy dependence of the thermal neutron flux could be obtained. The calculations took into account the density and temperature variation of the atmosphere as a function of depth and the presence of the ground. The atmosphere was assumed to be composed of 79% nitrogen and 21% oxygen and was approximated by a semi-infinite slab 1033-g-cm^{-2} thick. The ground was also approximated by a slab and was assumed to be SiO_2 . The galactic cosmic-ray proton and alpha-particle spectra were taken from the review article of McDonald,³⁹ and the effect of the geomagnetic fields at all angles of incidence was taken into account.⁴⁰

In Fig. 1 the calculated results are compared with the experimental data of Hess *et al.*³² The error bars on the calculated results, where shown, are statistical and represent one standard deviation. At the lower neutron energies (< 12 MeV), error bars are not given because the low-energy neutron transport calculations were not carried out with Monte Carlo techniques. At depths of 200 g cm^{-2} and 1033 g cm^{-2} , calculated results are shown for incident protons and for both incident protons and alpha particles to give an estimate of the effect of the alpha particles. The measured and calculated spectra differ somewhat at low energies, especially in the thermal energy region, but are in quite good agreement at the higher energies. The accuracy of the measured spectra at very low energies ($\leq 4 \times 10^{-8}$ MeV) is estimated by Hess *et al.*³² to be about a factor of 2.

Fig. 1. Omnidirectional (4π) neutron flux per unit energy at various depths from the top of the atmosphere (solar minimum, geomagnetic latitude = 42° N).

In considering the results, it must be remembered that the calculated results are absolute and have not in any way been normalized to the experimental data.

Recently Preszler *et al.*³⁶ made detailed measurements on the omnidirectional neutron flux per unit energy near the top of the atmosphere in the energy range of 10 to 100 MeV. In Fig. 2 the calculated results of Armstrong *et al.*⁹ are compared with these data.* Also shown are the earlier data of Hess *et al.* at a depth of 200 g cm⁻². The agreement between the calculated results and the experimental data of Preszler *et al.* is very good at all energies and depths considered.

B. Lateral Development of the Nucleon-Meson Cascade Induced in Iron by 29.4-GeV/c Protons⁴

In part A of section III, the longitudinal development of a nucleon-meson cascade was considered; that is, the properties of the cascade changed as a function of depth in the medium, but, because of the broad spatial extent of the incident proton and alpha-particle beams, the properties of the cascade could be assumed to be independent of position coordinates measured transversely to the depth coordinate. The lateral development of the nucleon-meson cascade induced in matter by a narrow beam of incident particles, which is of importance in some accelerator shielding applications, will now be considered. The lateral development of a cascade is much more dependent on the angular distribution of particles produced by nonelastic nuclear collisions than is the longitudinal development of a cascade, and, thus, the comparisons between calculated and experimental results presented here provide a more stringent test of the calculations than those presented in part A.

*Comparisons between calculated results and the experimental data of Preszler *et al.* have also been given by Merker.⁴¹

Fig. 2. Omnidirectional (4π) neutron flux per unit energy at various depths from the top of the atmosphere. (This figure is reprinted from Ref. 36 with permission.)

Van Ginneken and Borak⁴² have made measurements on the lateral development of the cascade induced in a very thick iron shield by a narrow beam of 29.4-GeV/c protons. The quantity measured was the production of ^{18}F in aluminum foils placed in the iron at various depths and at various distances from the axis of the incident proton beam.

Armstrong *et al.*⁴ carried out calculations with HETC and made comparisons between the calculated results and the experimental data of Van Ginneken and Borak.* In the experiment, the target was made up of slabs of iron of various thicknesses with air gaps between the slabs. These air gaps were taken into account in the calculations. The calculations were performed by first determining the energy and spatial distributions of the nucleon and charged-pion fluxes in the experimental configuration and then determining the ^{18}F production by using these fluxes in conjunction with the energy-dependent cross sections for the production of ^{18}F from aluminum by the various particles.⁴⁴ The energy dependence of these cross sections is such that the ^{18}F production may be interpreted as a measure of the nucleon and charged-pion fluxes above ~ 50 MeV.

Comparisons between the calculated and experimental results are shown in Figs. 3 (a), (b), and (c). The comparisons are absolute and unnormalized. The agreement is quite good although the calculations give a consistently higher production near the beam axis. Because of the small area and alignment of the aluminum foils used in the experiment, however, the experimental ^{18}F production is expected to yield an underestimate of the actual production very near the beam axis.⁴⁵

*Calculations have also been made for this experimental configuration by Van Ginneken and Borak⁴² using the code FLUTRA which is a modified version of a Monte Carlo code due to Ranft.⁴³

Fig. 3(a). Comparison of calculated and experimental⁴² lateral distributions of ^{18}F production in aluminum foils at various depths in iron for 29.4-GeV/c incident protons.

Fig. 3(b). Comparison of calculated and experimental⁴² lateral distributions of ^{18}F production in aluminum foils at various depths in iron for 29.4-GeV/c incident protons.

ORNL-DWG 71-14327

Fig. 3(c). Comparison of calculated and experimental⁴² lateral distributions of ^{18}F production in aluminum foils at various depths in iron for 29.4-GeV/c incident protons.

C. Energy-Deposition Fluctuations in an Iron-Liquid Scintillator Ionization Spectrometer⁴⁶

In part B of this section, the average properties of a nucleon-meson cascade were considered; i.e., the results presented were obtained by averaging over a large number of incident particles. Because of the statistical nature of the physical processes involved in the cascade, each incident particle of a given type and energy does not produce identical physical results, and for some applications the variation in the results produced by individual incident particles is of considerable importance. One such application which will now be considered is the performance of ionization spectrometers.

Basically, an ionization spectrometer is a collection of metal slabs interspersed with liquid scintillator slabs, which is used to measure the energy of high-energy protons and pions by measuring the light output from the liquid scintillators. The ability of the spectrometer to give an estimate of the energy of an incident particle of a given type is dependent on there being a unique relationship between the energy of the incident particle and the light output of the liquid scintillators. Such a unique relationship does not exist because of the variations in the energy deposition in the scintillator from individual incident particles of the same type, energy, direction, and initial coordinates. The validity of the energy estimate obtained from the spectrometer is, therefore, very dependent on the magnitude of the energy-deposition fluctuations, and thus a knowledge of the magnitude of these fluctuations is of considerable importance.

In Table I the composition and dimensions of the spectrometer considered are given. This spectrometer design and the experimental data pertaining to this design are due to Selove and his collaborators.⁴⁷ Gabriel

Table I
Spectrometer Design

Basic Cell	
Thickness (cm)	Material
0.32	Fe
3.81	Liquid Scintillator ^a
1.27	Fe
3.81	Liquid Scintillator ^a
1.27	Fe
3.81	Liquid Scintillator ^a
0.32	Fe

The spectrometer is composed of 15 basic cells. In front of the first cell, there is 0.95 cm of Fe and between each cell there are

0.71 cm	Void
1.91 cm	Lucite ^b
0.71 cm	Void

The lateral dimensions of the spectrometer are:

122 cm² by 122 cm²

a. CH₂, $\rho = 0.87 \text{ g cm}^{-3}$

b. C₅H₈O₂, $\rho = 0.944 \text{ g cm}^{-3}$

*et al.*⁴⁶ have carried out calculations with HETC for this design and have made comparisons between the calculated and experimental data. For this application, the transport of the high-energy photons from π^0 decay and the transport of the electrons and positrons from muon decay cannot be neglected. The code HETC does not transport these particles, but it does produce a source distribution, i.e., the energy, direction, and position of each type of particle, so they may be transported with another code. In obtaining the results presented here, the electron-photon cascade code of Beck⁴⁸ was used to transport the electrons, positrons, and photons produced by the cascade. In the calculations, the nonlinearity of the light pulse from the scintillators (i.e., the fact that the light observed is not directly proportional to the energy deposited) was taken into account by the use of Birks' law.⁴⁹ In the calculations and insofar as possible in the experiment, the incident particles were normally incident at the geometric center of the iron plate in front of the first cell.

In Figs. 4 and 5 calculated and experimental results for 15.0-GeV/c incident protons and positively charged pions, respectively, are presented and compared. The data shown indicate the frequency with which a given scintillator pulse height is produced as a function of pulse height. The calculated and experimental histograms in each case are normalized to the same number of incident particles in the pulse-height region over which experimental data are given. The error bars on the calculated histograms are statistical only and represent one standard deviation. In both cases, the calculated and experimental results are in good agreement, but in the case of incident pions, the calculated results are slightly larger than the experimental results for pulse heights of ~ 4500 MeV.

Fig. 4. Calculated and experimental pulse-height distribution for 15.0-GeV/c protons incident on a particular ionization spectrometer (see Table I).

Fig. 5. Calculated and experimental pulse-height distribution for 15.0-GeV/c positively charged pions incident on a particular ionization spectrometer (see Table I).

Additional results on calculated energy-deposition fluctuations and the performance of ionization spectrometers have been given by Gabriel and Chandler⁵⁰ and by Gabriel and Amburgey.⁵¹

D. Induced Activity in the Moon from Solar and Galactic Cosmic-Ray Bombardment⁵²

When a high-energy nucleon-meson cascade takes place in matter, a variety of residual nuclei are produced as a result of nonelastic nuclear collisions. The production of these residual nuclei is important in accelerator shielding as well as in a variety of other fields.^{53,54} In the case of accelerators, some of the radioactive residual nuclei produced in the cascade emit photons and thus present a potential radiation hazard after the accelerator has been turned off. Here, calculated results of the induced activity in the moon from solar and galactic cosmic-ray bombardment are presented as an example of induced-activity calculations performed with HETC. This example is chosen because of the availability of experimental data with which to compare the calculated results. The calculational method employed is, in principle, no different from that which has been used in calculating the induced activity in the vicinity of high-energy accelerators.⁵⁵⁻⁵⁷

As a result of the Apollo flights to the moon, experimental data on several radionuclides as a function of depth in the moon are available. Armstrong and Alsmiller⁵² have carried out calculations and made comparisons with these experimental data. The lunar composition and density used in the calculations were taken from Apollo 11 measurements for type D fine material.⁵⁸ The calculations were carried out for an isotropic flux of galactic or solar protons incident on a half-space of lunar material. The

galactic solar-minimum proton spectrum was taken from the review article of McDonald³⁹ and the galactic solar-maximum proton spectrum was taken from the wind-modulation theory of Durgaprasad *et al.*⁵⁹ The solar cosmic-ray proton data for solar cycle 19 were taken from the work of Modisette *et al.*⁶⁰ and of Weber,⁶¹ and for solar cycle 20 through November 1969 were taken from the work of Hsieh,⁶² Yucker,⁶³ Radke,⁶⁴ Baker,⁶⁵ and the compilation of the ESSA Research Laboratories.⁶⁶ In the calculations, it was assumed that the data for solar cycle 19 could be applied to all previous solar cycles. The solar and galactic cosmic-ray proton data used and a discussion of the manner in which the time dependence of the production and decay was taken into account are given in Ref. 67.

In Figs. 6(a) and 7(a), the calculated ^{26}Al and ^{22}Na activity, respectively, from galactic cosmic-ray protons at solar maximum and solar minimum and from solar cosmic-ray protons is shown as a function of depth. In Fig. 6(b), the total ^{26}Al activity, i.e., the sum of the solar contribution and the average of the galactic contributions at solar maximum and solar minimum, is compared with the activity measured by Shedlovsky *et al.*⁶⁸ and by Finkel *et al.*⁶⁹ In Fig. 7(b), the total ^{22}Na activity is compared with the activity measured by Shedlovsky *et al.*⁶⁸ In all of the figures, the activity is expressed in disintegrations per minute per kilogram. The ^{26}Al activity is nearly constant over a time interval of one solar cycle because of the long ^{26}Al half-life (7.4×10^5 y), but the ^{22}Na activity varies widely over a solar cycle because of the relatively short ^{22}Na half-life (2.62 y). The comparisons between the calculated and experimental data in Figs. 6(b) and 7(b) are absolute in the sense that there are no free parameters in the theory. The ^{26}Al activity for depths of ≤ 10 g cm⁻² is

Fig. 6. (a) ^{26}Al activity vs depth for incident solar and galactic cosmic-ray protons; (b) comparison of calculated and measured Al activity as a function of depth. (The Apollo 11 data are from Shedlovsky *et al.*⁶⁸ and the Apollo 12 data are from Finkel *et al.*⁶⁹)

Fig. 7. (a) Depth dependence of ^{22}Na activity from solar proton bombardment at the time of the Apollo 11 flight and from galactic proton bombardment; (b) comparison of calculated and measured ^{22}Na activity as a function of depth. (The Apollo 11 data are from Shedlovsky *et al.*⁶⁸)

due primarily to solar protons, whereas the activity at greater depths is due primarily to galactic protons. Therefore, the good agreement between the calculated and experimental results in Fig. 6(b) confirms the validity of the calculations for both solar and galactic protons. In general, the agreement between the calculated and experimental results in both Figs. 6(b) and 7(b) is quite satisfactory.

Additional comparisons between calculated induced activity and experimental data have been given by Armstrong.⁷⁰

E. Absorbed Doses and Cell-Survival Probabilities from Negatively Charged Pions^{71,72}

The code HETC has been used to calculate the energy deposition in tissue by a variety of charged-pion, neutron, and proton beams,⁷¹⁻⁷⁷ and results obtained with the code have, in general, been found to be in good agreement with experimental data.^{71,76,77} The usefulness of the code is not only that it gives a reliable estimate of the absorbed dose as a function of position in a phantom but also that it gives a complete description of all of the charged particles produced by nuclear interactions, and this information may be used to obtain the dose equivalent for radiation-protection purposes or may be combined with cell-inactivation models^{78,79} to obtain quantities of biomedical interest, such as cell-survival probabilities. As an example of these types of calculations, results are presented and compared with experimental data for the absorbed dose as a function of depth in a tissue phantom irradiated by a negatively charged pion beam and for the cell-survival probability as a function of absorbed dose in the capture region of a negatively charged pion beam.

Experimental data on the absorbed dose as a function of depth in a water phantom irradiated by a negatively charged pion beam with a mean momentum of 175 MeV/c (corresponding to a kinetic energy of 84 MeV) are available from Turner *et al.*⁸⁰ In the experiment, the pion beam was approximately elliptical in shape and was normally incident on one end of a water phantom. The absorbed dose was measured as a function of depth along the beam axis using a detector 3 cm in radius. The momentum spread of the beam was not measured precisely but was estimated to be Gaussian with a standard deviation of 4.7 MeV/c. The experimental π^- beam was contaminated with unmeasured numbers of negatively charged muons and electrons, and, thus, the measured absorbed-dose data contain contributions from these particles as well as from pions.

Using HETC for π^- and μ^- transport and the electron-photon cascade code of Beck⁴⁸ for e^- transport, calculations have been carried out by Armstrong and Chandler⁷¹ for comparisons with the experimental data.* In order to compare with the data, separate dose distributions for incident π^- , μ^- , and e^- beams were obtained, and the relative contribution of each type of particle to the measured absorbed-dose curve was determined by fitting the calculated results to the measured curve at three points. The absorbed dose is shown in Fig. 8 as a function of depth from the three different incident beams, and the comparison between the calculated and experimental data is shown in Fig. 9. Depths of 20.5, 28.5, and 35 cm were used to determine the relative number of each type of incident particle,

*Comparisons between calculated results, obtained using a different calculational procedure than that used by Armstrong and Chandler, and these experimental data have also been given by Turner *et al.*⁸¹

Fig. 8. Absorbed dose vs depth along the beam center line for π^- , μ^- , and e^- beams with a mean momentum of 175 MeV/c incident on a water phantom.

Fig. 9. Comparison of calculated and experimental absorbed dose from an incident π^- beam.

so the calculated and experimental results must agree at these points. The calculations indicated that the beam was composed of 71% π^- , 13% μ^- , and 16% e^- . The agreement between the calculated and experimental data in Fig. 9 is quite satisfactory, but the comparison is not definitive because of the fitting procedure needed to determine the beam contamination.

Katz *et al.* have developed a model of cell inactivation.^{78,79} Basically, this model allows a prediction of the probability that a given cell type will survive in any known radiation field no matter how complex, provided that the parameters in the model are available. These parameters, which must be determined from experimental data, are dependent on cell type and on whether the irradiation is carried out under aerobic or anoxic conditions. Parameters are presently available for a few cell types. The Katz *et al.* model, in conjunction with the data obtained from HETC, may be used to calculate cell-survival probabilities as a function of depth in a tissue phantom. A detailed discussion of the manner in which such calculations may be carried out has been given by Armstrong and Chandler.⁷²

Experimental data on the spatial dependence of cell-survival probabilities when various particles are incident on a phantom are not available at present for comparison with calculated results. There is, however, one experiment by Raju *et al.*⁸² in which the survival of T-1 kidney cells was measured at a single location in the stopping region of a pion beam. The measurements were made by placing T-1 kidney cells in the peak dose region of a contaminated pion beam (65% π^- , 10% μ^- , and 25% e^-) having a mean range of $\sim 23 \text{ g cm}^{-2}$ in lucite. Experimental cell-survival probabilities taken under both anoxic and aerobic conditions are shown in Fig. 10 as a function of absorbed dose. The experimental data show considerable spread because the experiment had to be performed with a very low intensity beam.

ORNL-DWG 73-2333R2

Fig. 10. Comparison of measured⁸² and calculated⁷² cell-survival probabilities in the capture region of a π^- beam.

Also shown in Fig. 10 are calculated results due to Armstrong and Chandler.⁷² Calculations using the experimental beam could not be made because the momentum spread of the beam was not measured. The results of Armstrong and Chandler were obtained using a pion beam which produced approximately uniform pion captures over the depth interval of 12.5 to 17.5 cm and the radial interval of 0 to 2.5 cm in tissue. The results shown in the figure are the cell-survival probabilities averaged over this capture region. While the conditions in the experiment and in the calculations are not completely equivalent, they are sufficiently similar to permit a valid comparison. Armstrong and Chandler did not perform detailed calculations on the effects of muon and electron contamination in the experimental beam, but they estimated the effects of these contaminants and found them to be small, as shown in Fig. 10. The agreement between the calculated and experimental results in Fig. 10 is quite satisfactory. Comparisons between calculated and experimental cell-survival probabilities are a much more stringent test of the calculations than are comparisons between calculated and experimental absorbed-dose data because the heavier, highly ionizing particles contribute very appreciably to the cell-survival probabilities, while they contribute only a small fraction of the absorbed doses.

Additional results on the use of various particles in cancer radiotherapy will be found in the references given above and in the work of Alsmiller *et al.*⁶³

REFERENCES

1. K. C. Chandler and T. W. Armstrong, "Operating Instructions for the High-Energy Nucleon-Meson Transport Code HETC," ORNL-4744, Oak Ridge National Laboratory (1972).
2. W. A. Coleman and T. W. Armstrong, "The Nucleon-Meson Transport Code NMTC," ORNL-4606, Oak Ridge National Laboratory (1970).
3. R. G. Alsmiller, Jr., T. W. Armstrong, and W. A. Coleman, Nucl. Sci. Eng. 42, 367 (1970).
4. T. W. Armstrong, R. G. Alsmiller, Jr., K. C. Chandler, and B. L. Bishop, Nucl. Sci. Eng. 49, 82 (1972).
5. D. C. Irving, R. M. Freestone, Jr., and F. B. K. Kam, "O5R, a General-Purpose Monte Carlo Neutron Transport Code," ORNL-3622, Oak Ridge National Laboratory (1965).
6. O. Ozer and D. Garber, "ENDF/B Summary Documentation," BNL-17541, National Cross Section Center, Brookhaven National Laboratory (1973).
7. R. W. Roussin, "Defense Nuclear Agency Working Cross Section Library," ORNL-RSIC-34, Vol. 1, Radiation Shielding Information Center, Oak Ridge National Laboratory (1972).
8. Miriam P. Guthrie, "EVAP-4: Another Modification of a Code to Calculate Particle Evaporation from Excited Compound Nuclei," ORNL-TM-3119, Oak Ridge National Laboratory (1970).
9. T. W. Armstrong, K. C. Chandler, and J. Barish, J. Geophys. Res. 78, 2715 (1973).
10. Wilmot N. Hess, Rev. Mod. Phys. 30, 368 (1958).
11. Hugo W. Bertini, Phys. Rev. 131, 1801 (1963) and erratum, Phys. Rev. 138, AB2 (1965).
12. V. S. Barashenkov, Interaction Cross Sections of Elementary Particles, 1966, Israel Program for Scientific Translation, Jerusalem, 1968.
13. T. A. Gabriel, R. T. Santoro, and J. Barish, "A Computational Method for Predicting Particle Spectra from High-Energy Nucleon and Pion Collisions (≥ 3 GeV) with Protons," ORNL-TM-3615, Oak Ridge National Laboratory (1971).
14. F. D. Becchetti, Jr. and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).
15. C. M. Perey and F. G. Perey, Atomic Data and Nuclear Data Tables 13, 293 (1974).

16. H. W. Bertini, M. P. Guthrie, and O. W. Hermann, "Instructions for the Operation of Codes Associated with MECC-3, a Preliminary Version of an Intranuclear-Cascade Calculation for Nuclear Reactions," ORNL-4564, Oak Ridge National Laboratory (1971).
17. H. W. Bertini, "Monte Carlo Calculations on Intranuclear Cascades," ORNL-3383 (Dissertation), Oak Ridge National Laboratory (1963).
18. V. A. Konshin and E. S. Matusevich, Atomic Energy Review 6, 3 (IAEA 1968).
19. H. W. Bertini, Phys. Rev. 188, 1711 (1969).
20. H. W. Bertini, Phys. Rev. C 6, 631 (1972).
21. V. S. Barashenkov *et al.*, Nucl. Phys. A187, 531 (1972).
22. R. G. Alsmiller, Jr. and O. W. Hermann, Nucl. Sci. Eng. 40, 254 (1970).
23. Hugo W. Bertini, Phys. Rev. C 5, 2118 (1972).
24. F. E. Bertrand and R. W. Peelle, Phys. Rev. C 8, 1045 (1973).
25. H. W. Bertini, G. D. Harp, and F. E. Bertrand, Phys. Rev. C 10, 2472 (1974).
26. M. P. Guthrie, R. G. Alsmiller, Jr., and H. W. Bertini, Nucl. Instr. Meth. 66, 29 (1968); with erratum, Nucl. Instr. Meth. 91, 669 (1971).
27. T. A. Gabriel, R. G. Alsmiller, Jr., and M. P. Guthrie, "An Extrapolation Method for Predicting Nucleon and Pion Differential Production Cross Sections from High-Energy (> 3 GeV) Nucleon-Nucleus Collisions," ORNL-4542, Oak Ridge National Laboratory (1970).
28. T. A. Gabriel and R. T. Santoro, "Calculation of the Long-Lived Activity in Soil Produced by 500-GeV Protons," ORNL-TM-3262, Oak Ridge National Laboratory (1970).
29. S. F. Singer, Phys. Rev. Lett. 1, 181 (1958).
30. A. J. Dragt, M. M. Austin, and R. S. White, J. Geophys. Res. 71, 1293 (1966).
31. T. A. Farley and M. Walt, J. Geophys. Res. 76, 8223 (1971).
32. W. N. Hess, H. W. Patterson, R. Wallace, and E. L. Chupp, Phys. Rev. 116, 445 (1959).
33. S. S. Holt, R. B. Mendell, and S. A. Korff, J. Geophys. Res. 71, 5109 (1966).

34. E. Heidbreder, K. Pinkau, C. Reppin, and V. Schönfelder, J. Geophys. Res. 75, 6347 (1970).
35. A. M. Preszler, G. M. Simnett, and R. S. White, Phys. Rev. Lett. 28, 982 (1972).
36. A. M. Preszler, G. M. Simnett, and R. S. White, J. Geophys. Res. 79, 17 (1974).
37. T. A. Gabriel, R. T. Santoro, and R. G. Alsmiller, Jr., Nucl. Sci. Eng. 44, 104 (1971).
38. W. W. Engle, Jr., "A Users Manual for ANISN, a One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering," K-1693, Computing Technology Center, Union Carbide Corporation (1967).
39. F. B. McDonald, "IQSY Observations of Low-Energy Galactic and Solar Cosmic Rays," in Annals of the IQSY, Vol. 4, edited by A. C. Strickland, MIT Press, Cambridge, Massachusetts, 1969, pp. 187-216.
40. T. W. Armstrong, K. C. Chandler, and J. Barish, "Calculations of Neutron Flux Spectra Induced in the Earth's Atmosphere by Galactic Cosmic Rays," ORNL-TM-3961, Oak Ridge National Laboratory (1972).
41. M. Merker, Phys. Rev. Lett. 29, 1531 (1972).
42. A. Van Ginneken and T. Borak, IEEE Trans. Nucl. Sci., NS-18, 3, 746 (1971).
43. J. Ranft, Nucl. Instr. Meth. 48, 261 (1967).
44. T. W. Armstrong and R. G. Alsmiller, Jr., Nucl. Sci. Eng. 33, 291 (1968).
45. A. Van Ginneken, National Accelerator Laboratory, private communication (1971).
46. T. A. Gabriel, J. D. Amburgey, and R. T. Santoro, "Calculated Performance of a Mineral-Oil-Iron Ionization Spectrometer," ORNL-TM-4803, Oak Ridge National Laboratory (1975).
47. W. Selove, University of Pennsylvania, private communication.
48. H. L. Beck, "A Monte Carlo Simulation of the Transport of High Energy Electrons and Photons in Matter," HASL-213, USAEC Health and Safety Laboratory (1969).
49. J. B. Birks, The Theory and Practice of Scintillation Counting, The Macmillan Company, New York, 1964.
50. T. A. Gabriel and K. C. Chandler, Particle Accelerators 5, 161 (1973).
51. T. A. Gabriel and J. D. Amburgey, Nucl. Instr. Meth. 116, 333 (1974).

52. T. W. Armstrong and R. G. Alsmiller, Jr., Proc. Apollo 12 Lunar Science Conf., Geochim. Cosmochim. Acta, Vol. 2, Suppl. 2, p. 1729, MIT Press, Cambridge, Massachusetts (1971).
53. D. Lal and B. Peters, "Cosmic Ray Produced Radioactivity on the Earth," Encyclopedia of Physics, Vol. XLVI/2, pp. 551-612, K. Sitte, Ed., Springer-Verlag, Berlin, Heidelberg, New York (1967).
54. M. Honda and J. R. Arnold, "Effects of Cosmic Rays on Meteorites," Encyclopedia of Physics, Vol. XLVI/2, pp. 613-631, K. Sitte, Ed., Springer-Verlag, Berlin, Heidelberg, New York (1967).
55. T. W. Armstrong and R. G. Alsmiller, Jr., Nucl. Sci. Eng. 38, 53 (1969).
56. T. A. Gabriel, Nucl. Instr. Meth. 91, 67 (1971).
57. T. A. Gabriel and R. T. Santoro, Nucl. Instr. Meth. 95, 275 (1971).
58. LSPET (Lunar Sample Preliminary Examination Team), Science 165, 1211 (1969).
59. N. Durgaprasad, C. E. Fichtel, and D. E. Guss, J. Geophys. Res. 72, 2765 (1967).
60. J. L. Modisette, T. M. Vinson, and A. C. Hardy, "Model Solar Proton Environments for Manned Spacecraft Design," NASA TN D-2746, National Aeronautics and Space Administration (1965).
61. W. R. Webber, "An Evaluation of the Radiation Hazard Due to Solar-Particle Events," D2-90469, Boeing (1963).
62. K. C. Hsieh, private communication (1970).
63. W. R. Yucker, "Statistical Analysis of Solar Cosmic Ray Proton Fluence," MDAC Paper WD 1320, McDonnell Douglas Astronautics (1970).
64. G. Radke, Aerospace Med. 40, 1495 (1969).
65. M. B. Baker, R. E. Santana, and A. J. Masley, A.I.A.A.J. 7, 2105 (1969).
66. ESSA (ESSA Research Laboratories), "Solar-Geophysical Data," Report No. 309, Part II, Environmental Research Laboratories (1970).
67. T. W. Armstrong and R. G. Alsmiller, Jr., "Calculation of Cosmogenic Radionuclides in the Moon and Comparison with Apollo Measurements," ORNL-TM-3267, Oak Ridge National Laboratory (1970).
68. J. P. Shedlovsky *et al.*, Proc. Apollo 11 Lunar Science Conf., Geochim. Cosmochim. Acta, Vol. 2, Suppl. 1, p. 1503, Pergamon Press, New York (1970).

69. R. C. Finkel *et al.*, Proc. Apollo 12 Lunar Science Conf., Geochim. Cosmochim. Acta, Vol. 2, Suppl. 2, p. 1773, MIT Press, Cambridge, Massachusetts (1971).
70. T. W. Armstrong, J. Geophys. Res. 74, 1361 (1969).
71. T. W. Armstrong and K. C. Chandler, Radiat. Res. 52, 247 (1972).
72. T. W. Armstrong and K. C. Chandler, Radiat. Res. 58, 293 (1974).
73. R. G. Alsmiller, Jr., T. W. Armstrong, and W. A. Coleman, Nucl. Sci. Eng. 42, 367 (1970).
74. R. G. Alsmiller, Jr., T. W. Armstrong, and Barbara L. Bishop, Nucl. Sci. Eng. 43, 257 (1971).
75. T. W. Armstrong, R. G. Alsmiller, Jr., and K. C. Chandler, Phys. Med. Biol. 18, 830 (1973).
76. T. W. Armstrong and B. L. Bishop, Radiat. Res. 47, 581 (1971).
77. R. G. Alsmiller, Jr. and J. Barish, Med. Phys. 1, 51 (1974); with erratum to be published.
78. R. Katz, S. C. Sharma, and M. Homayoonfar, Chap. 6 in Topics in Radiation Dosimetry, Suppl. 1 to Radiation Dosimetry, edited by Frank A. Attix, Academic Press, New York (1972).
79. Robert Katz and S. C. Sharma, Nucl. Instr. Meth. 111, 93 (1973).
80. J. E. Turner *et al.*, Proc. Intl. Congress on Protection Against Accelerator and Space Radiation, Vol. 1, p. 231, April 26-30, 1971, CERN, Geneva, Switzerland, CERN 71-16.
81. J. E. Turner *et al.*, Radiat. Res. 52, 229 (1972).
82. M. R. Raju *et al.*, Brit. J. Radiol. 45, 178 (1972).
83. R. G. Alsmiller, Jr., *et al.*, Radiat. Res. 60, 369 (1974).