CONF-820688--3

DE83 014031

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**NUCLEON-MESON TRANSPORT CAPABILITY *
FOR ACCELERATOR-BREEDER TARGET DESIGN**

*T. A. Gabriel and R. G. Alsmiller, Jr.
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830*

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* Research supported by the Office of High Energy & Nuclear Physics, U. S. Department of Energy under contract no. W-7405-eng-26 with Union Carbide Corporation.

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ABSTRACT

A state-of-the-art code system for nucleon-meson-lepton transport which has direct applicability to accelerator breeders is presented. Some pertinent data that have been obtained using this system are discussed and compared with experimental data.

I. INTRODUCTION

Accelerator breeders offer an exciting alternative to fast breeder reactors for the production of fissile material from fertile material.¹ However, without established and dependable radiation transport capabilities, design of an optimum breeder which is economically feasible would be very difficult, if not impossible. The main purpose of this paper is to describe an established and dependable program package, CALOR,^{2,3,4,5} and associated support codes and data that have been developed for general use in high-energy radiation transport calculations, and that have direct applicability to accelerator breeders. In addition, some calculated data that have been obtained with CALOR and which are directly applicable to accelerator breeders will also be presented.

II. CALOR: GENERAL DESCRIPTION

The three-dimensional multimedia high-energy nucleon-meson transport code, HETC,³ is the heart of the CALOR system for incident hadrons and is used with slight modification to obtain a detailed description of the nucleon-meson cascade produced in energy absorbing systems. This Monte Carlo code takes into account the slowing down of the charged particles via the continuous slowing-down approximation, the decay of charged pions

and muons, inelastic nucleon-nucleus and charged-pion-nucleus (excluding hydrogen) collisions through the use of the intermediate energy intranuclear-cascade-evaporation (MECC) model,⁶ and inelastic nucleon-hydrogen and charged-pion-hydrogen collisions via the isobar model.* Also accounted for are elastic neutron-nucleus collisions and elastic nucleon- and charged-pion collisions with hydrogen. Recently, the HETC code has been improved by the inclusion of a detailed fission model⁷ and by the inclusion of the combinatorial geometry package.

The source distribution for the electromagnetic cascade calculation (i.e., photons from neutral pion decay, electrons and positrons from muon decay, and deexcitation gamma rays from the decay of excited nuclei) is provided by the results of HETC. The transport of these particles is carried out by using a modified version of the three-dimensional multimedia Monte Carlo code, EGS,⁴ developed by Ford and Nelson. This code takes into account all of the significant electron, positron, and photon-interaction processes, i.e., Compton scattering, pair production, bremsstrahlung, photoelectric effect, annihilation, the slowing down of electrons and positrons due to ionization and excitation, etc. As with HETC, the CALOR version of EGS code utilizes the combinatorial geometry package.

In most applications using HETC, neutrons are transported if their energy is above ~15-20 MeV. Neutrons produced below this cutoff energy are transported using the multimedia three-dimensional multigroup neutron and gamma-ray Monte Carlo transport code, MORSE.⁵ This code is noted for the following features: 1) use of multigroup cross section sets usually

* Different methods are used for particle energies ≥ 3 GeV.

processed from ENDFB/V data; 2) inclusion of anisotropic scattering and time-dependence; 3) utilization of the combinatorial geometry package; and 4) in contrast to EGS and HETC, incorporation of statistical biasing and importance sampling techniques.

In situations where the dimensionality of the system can be reduced to two or one, the discrete ordinates codes DOT⁸ or ANISN⁹ can be used to obtain transport results associated with the low-energy neutrons. These codes are extremely valuable when large transport distances are involved.

There are many support codes and data systems which can be of assistance when using the CALOR system. A few of these include: SPECT,² a code to calculate energy deposition from the results obtained by HETC; MAGIK,¹⁰ a code to calculate residual activation dose; PEGS,⁴ a code to calculate cross sections for EGS; HILO,¹¹ a multigroup neutron and gamma-ray cross section library for neutron energies up to 400 MeV, and gamma-ray energies up to 15 MeV; AMPX,¹² a computer code system to calculate multigroup cross section data sets for MORSE (or DOT and ANISN) from ENDFB data, etc.

III. APPLICATIONS

The CALOR system, or parts of the system, has been used to study many high-energy particle accelerator systems (in particular, neutron spallation sources) which are closely related to accelerator breeders. For example, the IPNS at Argonne National Laboratory, the SNS at the Rutherford Laboratory, and the SNQ at Julich, West Germany are being designed using CALOR. In addition, accelerator breeding calculations have been carried out for preliminary

assessment considerations. The results of this work have been published as Ref. 1.

Since accelerator breeders depend on maximizing neutrons produced and neutrons captured by fertile material and minimizing the energy required to produce each neutron, some of the first experimental and calculated results dealt with these topics. Some of these first results are summarized in Figs. 1^{13,*} and 2^{13,*} and Table 1.¹⁴ Obviously, from Fig. 1 the larger atomic number targets produce larger numbers of neutrons when GeV energy protons are incident. If the material has a fission probability, an increase of ~ 2 in the number of neutrons produced can be obtained. To minimize the energy (see Fig. 2) needed per neutron produced requires that the incident particle (in this case incident protons) have an energy of 1 GeV or slightly higher.

The calculated results of the number of neutron captures in ^{235}U and ^{238}U and the total number of fission for 1 and 2 GeV protons incident on an infinite natural uranium target are presented in Table 1. Table 1 presents a rather glamorous picture for accelerator breeders. For each GeV of proton energy incident, the system generated 5 GeV in energy which can possibly be used for some immediate power generation, and ~ 16 GeV of future potential energy due to the neutron captures in ^{238}U . However, if the calculations are carried out for a more realistic breeder target design such as the one considered in the ABACS report these numbers immediately drop by more than a factor of two. Still, the results indicate that accelerator breeders offer much hope for the production of fuel. Also shown in Table 1 are comparisons with data generated by Barashenkov et al.¹⁵ They have recently revised their fission model¹⁶ and new results (even though $\sim 10\%$ higher) are now more consistent with the results obtained with CALOR.

* Experimental results.

NEUTRON YIELD AS A FUNCTION OF TARGET MATERIAL AND PROTON ENERGY

Fig. 1

ENERGY REQUIRED TO LIBERATE LOW-ENERGY NEUTRONS BY HIGH-ENERGY
PROTON BOMBARDMENT OF Pb TARGET

Fig. 2

Table 1

CALCULATED RESULTS FOR 1 AND 2 GEV PROTONS INCIDENT ON AN INFINITE URANIUM TARGET (ALL RESULTS ARE GIVEN PER INCIDENT PROTON)

INCIDENT PROTON ENERGY	CAPTURES IN ^{235}U	CAPTURES IN ^{238}U	TOTAL FISSIONS	TOTAL ENERGY DEPOSITION (GeV)
1.0	1.1 ± 0.1 (1.2) ^a	84.9 ± 2.7 (101.)	23.1 ± 0.7 (28.3)	5.11 ± 0.13
2.0	2.0 ± 0.2 (2.5)	$154. \pm 15.$ (203.)	43.1 ± 3.4 (60.1)	11.1 ± 0.8

^aCalculated by V. S. Barashenkov et al.

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1.0	—	41.0	5.8	2.04
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G. J. Russell and his collaborators¹⁷ at the Los Alamos National Laboratory have recently carried out a series of measurements for the case of 800 MeV protons incident on a variety of thick targets. In particular, they have measured the total number of thermal neutron captures in a large water bath surrounding several thick depleted uranium targets. In Fig. 3 a schematic diagram of the experimental arrangement is shown. Two different uranium targets were considered.

Experimental thermal neutron capture measurements similar to those conducted by G. J. Russell et al., have been carried out by J. S. Fraser et al.¹⁸ using 480 MeV incident protons. The experimental geometry differed in detail from that in Fig. 3, but was not qualitatively different.

In carrying out the calculations to obtain results for comparison with G. J. Russell et al., the geometry in Fig. 3 was used. A similar geometry with dimensions taken from Ref. 18 was used to obtain the results for comparison with the data of J. S. Fraser et al. In those cases where the target was composed of closely packed cylindrical rods the target was approximated by a central cylinder (one rod) surrounded by two cylindrical annuli with different uranium densities to take into account the void regions. The proton beam profile used in the calculations was, in all cases, that determined experimentally.

In Table 2 the calculated¹⁴ and experimental number of thermal neutron captures in the water is given. Also given in Table 2 for comparison purposes are the calculated results of J. S. Fraser et al.¹⁸ The error bars on the calculated results are statistical only and represent one standard

Fig. 3. Schematic diagram of the geometry used by G. J. Russell et al.¹⁵

deviation. The calculated results obtained here are in good agreement with the results for 800 MeV incident protons, but do not agree well with the data for 480 MeV incident protons. The calculations overestimate the value for the small radius target for 480 MeV incident protons and underestimate the value for the large radius target for 480 MeV incident protons. The calculations of J. S. Fraser et al. were carried out using NMTC which is an early version of the code HETC used here. Since in the NMTC calculations, all high-energy fission is neglected, the difference between the two calculations may be attributed to the effects of high-energy fission. However, since the pion production data in HETC is different from that in NMTC, and the value of the level density parameter for the evaporation phase of the calculation B_0 used in obtaining the results in Ref. 18 may be different from the value 10 MeV used here, the difference between the two calculations may not be due entirely to the effects of high-energy fission.

Experimental measurements of the number of thermal neutron captures in water for protons with a variety of energies incident on a depleted uranium target have also been reported by J. S. Fraser et al.^{19,20} The experimental geometry in this series of measurements was again qualitatively similar to that shown in Fig. 3. In these experiments the number of thermal neutron captures in water was measured by essentially the same technique that was used to obtain the results in Table 2. Experimental results were obtained for incident proton energies of 540, 720, 970 and 1470 MeV.

Calculated results¹⁴ for comparisons with these data have been obtained using the dimensions and material compositions given in Ref. 19. In Fig. 4 the experimental and calculated results are compared. It should be noted

Table 2

Thermal Neutron Captures in Water (see Fig. 1)
for Protons Incident on Uranium Targets

Uranium Target	Thermal Neutron Captures in Water per Incident Proton [captures (incident proton) ⁻¹]		
	800 MeV Incident Protons		
	<u>Experimental</u> ¹⁷	<u>Calculated</u>	
Cylinder with radius 5.00 cm	25.3	27.2 _{+1.2}	
37 close-packed rod target*	28.8	28.6 _{+0.8}	
	480 MeV Incident Protons		
	<u>Experimental</u> ¹⁸	<u>Calculated</u>	
		<u>Here</u>	<u>Ref. 18</u>
Cylinder with radius 1.626 cm	9.6 _{+0.7}	11.8 _{+0.4}	10.1 _{+0.4}
37 close-packed rod target	17.1 _{+1.0}	14.1 _{+0.6}	12.3 _{+0.4}

that the experimental data in Fig. 4 is the number of thermal neutron captures in the water and not the total neutron yield that is often quoted.* To obtain this total neutron yield, a very difficult to estimate correction for neutron captures in the uranium target is needed.

The calculated results are in good agreement with the experimental data for all incident proton energies ≤ 960 MeV, but the calculated number of thermal neutron captures is significantly larger than the experimental value for 1470 MeV incident protons. Since there is a significant discrepancy between the calculated and experimental results for 1470 MeV incident protons, calculated results have been obtained for the case for $B_0 = 15$ MeV. The calculated value obtained in this case is also shown in Fig. 4. The calculated value obtained with $B_0 = 15$ MeV is substantially smaller than the calculated value obtained with $B_0 = 10$ MeV, but is still somewhat larger than the experimental value. The reason for this discrepancy is not known. If the experimental data are taken to be correct then it must be concluded that the cross section model used here becomes invalid for incident proton energies much above 1 GeV or at least a value for the level density parameter B_0 substantially larger than 10 MeV must be used at the higher (~ 1.5 GeV) incident energies.

The calculation of the production of residual nuclei (especially fission products) due to hadronic cascades is a very difficult one, but a necessary one if activation results are to be obtained. Presented in Fig. 5 is a normalized comparison between the calculated fission fragments produced

* The experimental data in Fig. 4 was supplied by Dr. P. Garvey of the Chalk River Nuclear Laboratory. Thanks are due to Dr. Garvey for making these data available.

Fig. 4. Thermal neutron captures in water for protons of several energies incident on a cylindrical uranium target.

when 30 MeV protons are incident on a ^{235}U target. The agreement in shape is quite good. Other comparisons⁷ have been made at higher energies with reasonable agreement between calculated and experimental data. The fission model incorporated into HETC (even though there are areas which need improving) seems to work quite well.

IV. SUMMARY AND CONCLUSIONS

A calculational procedure, CALOR, has been presented that can be used today to provide realistic design data relating to accelerator breeders. Although there are areas in which substantial research and code improvement and development could be made, the code system has the capability of providing data, and in many areas calculated results which are in very good agreement with experimental data.

RESIDUAL NUCLEI DISTRIBUTION PER MASS NUMBER PER NONELASTIC
COLLISION VS. MASS NUMBER FOR 30 MEV PROTONS ON ^{235}U .

Fig. 5

References

1. "Preliminary Report on the Promise of Accelerator Breeding and Converter Reactor Symbiosis (ABACS) as an Alternative Energy System," ORNL/TM-5750, Oak Ridge National Laboratory (1977).
2. T. A. Gabriel, J. D. Amburgey, and B. L. Bishop, "CALOR: A Monte Carlo Program Package for the Design and Analysis of Calorimeter Systems," ORNL/TM-5619, Oak Ridge National Laboratory (1977).
3. T. W. Armstrong and K. C. Chandler, "Operating Instructions for the High-Energy Nucleon-Meson Transport Code, HETC," ORNL-4744, Oak Ridge National Laboratory (1972).
4. R. L. Ford and W. R. Nelson, "The EGS Code System: Computer Programs for the Monte Carlo Simulation of Electromagnetic Cascade Showers," SLAC-210, Stanford Linear Accelerator Center (1978).
5. E. A. Straker et al., "The MORSE Code — A Multigroup Neutron and Gamma Ray Monte Carlo Transport Code," ORNL-4585, Oak Ridge National Laboratory (1970).
6. H. W. Bertini, Phys. Rev. C6, 631 (1972).
7. F. S. Alsmiller et al., "A Phenomenological Model for Particle Production from the Collisions of Nucleons and Pions with Fissile Elements at Medium Energies," ORNL/TM-7528, Oak Ridge National Laboratory (1981).
8. W. A. Rhoades et al., "The DOT IV Two-Dimensional Discrete Ordinates Transport Code With Space-Dependent Mesh and Quadrature," ORNL/TM-6529, Oak Ridge National Laboratory (1979).
9. W. W. Engle, Jr., "A Users Manual for ANISN: A One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering," K1693, Oak Ridge Gaseous Diffusion Plant (1967).
10. J. Barish, T. A. Gabriel and R. G. Alsmiller, Jr., "MAGIK — A Monte Carlo System for Computing Induced Residual Activation Dose Rates," ORNL-5561, Oak Ridge National Laboratory (1979).
11. R. G. Alsmiller, Jr. and J. Barish, "Neutron-Photon Multigroup Cross Sections for Neutron Energies ≤ 400 Mev," Nucl. Sci. Eng. 80, 448 (1982)

References(Cont'd)

12. N. M. Greene et al., "AMPX: A Modular Code System for Generating Coupled Multigroup n and γ Libraries from ENDFB," ORNL/TM-3706, Oak Ridge National Laboratory (1976).
13. W. A. Gibson et al., "Low-Energy Neutron Production by High-Energy Proton Bombardment of Thick Targets," Electronuclear Division Annual Progress Report for Period Ending December 31, 1965, ORNL-3940, Oak Ridge National Laboratory (1966).
14. R. G. Alsmiller, Jr. et al., "Neutron Production by Medium-Energy (≤ 1.5 GeV) Protons in Thick Uranium Targets," ORNL/TM-7527, Oak Ridge National Laboratory (1981).
15. V. S. Barashenkov, V. D. Toneev, and S. E. Chigrinov, "On the Calculation of Electronuclear Neutron Generation," Soviet Atomic Energy 37, 1251 (1974).
16. Private communication, V. S. Barashenkov ().
17. G. J. Russell et al., "Spallation Target-Moderation-Reflector Studies at the Weapons Neutron Research Facility," published in the Proceedings of the Symposium on Neutron Cross Sections From 10-50 MeV, May 12-14, 1980, Brookhaven National Laboratory.
18. J. S. Fraser et al., "Neutron Production in Thick Targets in Lead, Thorium and Uranium Bombarded by 480 MeV Protons," published in the Proceedings of the Symposium on Neutron Cross Sections From 10-50 MeV, May 12-14, 1980, Brookhaven National Laboratory.
19. J. S. Fraser et al., "Neutron Production in Thick Targets Bombarded by High-Energy Protons," Phys. in Canada 21, 17 (1975).
20. G. A. Bartholomew and P. R. Tunncliffe, "The AECL Study for the Intense Neutron Generator," Atomic Energy of Canada Limited Report AECL-2600, VII-11 (1966).