LA-UR- 95-817

Conf-950777--2

Title: INTRODUCTION TO SPALLATION PHYSICS AND SPALLATION-
TARGET DESIGN

Author(s): G. J. Russell, E. J. Pitcher, L. L. Daemen

Submitted to: International Conference on Accelerator-Driven
Transmutation Technologies and Applications,
Las Vegas, NV, 25-29 July 95

RECEIVED
MAR 10 1995
OSTI

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Form No. 836 R5
ST 2629 10/91

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make 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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Introduction to Spallation Physics and Spallation-Target Design

G. J. Russell, E. J. Pitcher, and L. L. Daemen

Manuel Lujan, Jr. Neutron Scattering Center

LANSCe, MS H805, P.O. Box 1663

Los Alamos National Laboratory

Los Alamos, NM 87545 U.S.A.

Abstract. When coupled with the *spallation* process in appropriate target materials, high-power accelerators can be used to produce large numbers of neutrons, thus providing an alternate method to the use of nuclear reactors for this purpose. Spallation offers exciting new possibilities for generating intense neutron fluxes for a variety of applications, including: (a) spallation-neutron sources for materials science research; (b) accelerator-based production of tritium; (c) accelerator-based transmutation of waste; (d) accelerator-based destruction of plutonium; and (e) radioisotope production for medical and energy applications. Target design plays a key role in these applications, with neutron production/leakage being strongly dependent on the incident particle type and energy, and target material and geometry.

INTRODUCTION

Nuclear transmutation was first demonstrated by Rutherford in 1919, who changed ^{14}N to ^{17}O using energetic alpha particles [1]. I. Curie and F. Joliot produced the first artificial radioactivity in 1933. They used alpha particles from naturally radioactive isotopes to transmute boron and aluminum (both light elements) into radioactive nitrogen and oxygen. It was not possible to extend this type of transmutation to heavy elements as long as the only available charged particles were the alpha particles from natural radioactivity, because the Coulomb barriers surrounding heavy nuclei are too great to permit the entry of such particles into atomic nuclei. The invention of the cyclotron by E. O. Lawrence [2], and the later construction and operation of high-power accelerators such as the Clinton P. Anderson Meson Physics Facility (LAMPF) [3] removed this barrier. (LAMPF, located at the Los Alamos National Laboratory [LANL], is the highest-power accelerator in the world, producing 1 mA of 800-MeV protons).

When coupled with the *spallation* process, high-power accelerators can be used to produce large numbers of neutrons, thus providing an alternate method to the use of nuclear reactors for this purpose. Spallation offers exciting new possibilities for generating intense neutron fluxes for a variety of applications. We will discuss basic spallation target physics, the calculational tools used at Los Alamos to simulate spallation, the fundamentals of spallation-target design, and the development of the split-composite target concept. Spallation is being considered for various applications including: (a) spallation-neutron sources for materials science research; (b) accelerator-based production of tritium; (c) accelerator-based transmutation of waste; (d) accelerator-based destruction of plutonium; and (e) radioisotope production for medical and energy applications.

WHAT IS SPALLATION, ANYWAY?

Spallation refers to nuclear reactions that occur when energetic particles (e.g., protons, deuterons, neutrons, pions, muons, etc.) interact with an atomic nucleus (the "target" nucleus). In this context, "energetic" means kinetic energies larger than about 100 MeV per nucleon. At these energies (where the deBroglie wavelength of the incident particle is short enough to allow the incident particle to interact with individual nucleons inside the nucleus), it is no longer correct to think of the nuclear reaction as proceeding through the formation of a compound nucleus. The initial collision between the incident projectile and the target nucleus leads to a series of direct reactions (intranuclear cascade) whereby individual nucleons or small groups of

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GL

MASTER

nucleons are ejected from the nucleus. At energies above a few GeV per nucleon, fragmentation of the nucleus can also occur. After the intranuclear cascade phase of the reaction, the nucleus is left in an excited state. It subsequently relaxes to its ground state by "evaporating" nucleons, mostly neutrons.

The spallation process is depicted in Fig. 1, showing two stages of the process (intranuclear cascade and evaporation). For thick targets, high-energy (≥ 20 MeV) secondary particles (plus their progeny) can undergo further spallation reactions. For some target materials, low-energy (≤ 20 MeV) spallation neutrons (i.e., the cascade-evaporation neutrons) can enhance neutron production through low-energy (n,xn) reactions. For heavier nuclei, high-energy fission can compete with evaporation in a highly-excited nucleus. High-energy fission competition with evaporation in a highly-excited nucleus is illustrated in Fig. 1. Tantalum, tungsten, and lead are examples of materials that can undergo spallation/high-energy fission.

Some spallation-target fissionable materials such as thorium and depleted uranium can (in addition to undergoing high-energy fission) be fissioned by low-energy (~ 1 MeV to ~ 20 MeV) neutrons. Spallation, high-energy fission, and low-energy neutron fission produce different nuclear debris (spallation and fission products) as discussed below.

Fig. 1. Illustration of the spallation process in thick targets, with evaporation competing with high-energy fission in the de-excitation of highly-excited nuclei.

How Does Spallation Differ From Fission?

In The Number Of Low-Energy Neutrons Produced

Spallation and fission differ in several ways. One difference is in the number of (potentially) useful low-energy neutrons produced per spallation or fission event. The number of neutrons produced per fission event (about 2.5) is considerably less than that produced in spallation of heavy nuclei (typically in the tens of neutrons, depending on target material and size, and incident particle type and energy). Furthermore, one of the 2.5 neutrons produced by fission is needed to sustain the fission reaction; this neutron, therefore, is not available for other uses.

In The Amount Of Energy Deposited Per Neutron Produced

Spallation and fission also differ in the amount of energy deposited per (useful) neutron produced. For fission, about 180 MeV of energy is deposited in the reactor core per fission event, or about 120 MeV per useful neutron produced. For spallation (in an infinite tungsten target bombarded by 1000-MeV protons), the corresponding number is about 25 MeV. Power density in a reactor core limits the neutron flux that can be realized in a practical sense from fission reactors. The spallation process (by itself) is much more efficient than fission in this regard. Although there is less heat generated with spallation, the intensity of the incident particle beam (particles/cm²) for a high-power spallation source can lead to cooling problems—equivalent to those of a high-power reactor source—in windows and targets, unless special care is taken.

In The Amount Of Gamma-Ray Energy Produced

For infinite tungsten and lead targets bombarded by 1000-MeV protons, ~3 MeV of gamma-ray energy is emitted for each neutron produced; about 12 MeV is released per fission event. Because spallation-neutron sources do not produce as much gamma-ray energy as equivalent reactor sources, gamma-ray heating problems in materials at a spallation source are less problematic than those at a reactor source. This difference can be important in practical applications—for example, when designing cold neutron sources for basic materials science research.

In The Energy Distribution Of The Neutrons Produced

On average, spallation neutrons have higher energies than fission neutrons. In a spallation source, high-energy secondary neutrons approach the energy of the incident particle. High-energy neutrons are extremely penetrating. Well-designed shielding is needed to prevent the escape of high-energy neutrons from the spallation-source environment. Also, the production of high-energy neutrons is angle-dependent, with higher-energy neutrons being generated in the forward direction. High-energy neutrons are useful for nuclear physics research, radiography, and in helping to understand radiation damage in a spallation environment. The low-energy neutrons are produced (more or less) isotropically.

In The Nuclear Debris Created

For low-energy neutron fission, the nucleus divides in two, typically producing a light fragment and a heavy fragment as fission products. For high-energy fission, the fission products

are more symmetric in their mass distribution than the asymmetric fission products caused by lower-energy particles. In spallation, the products created (nuclear debris) are distributed close to the original target material. The distribution of spallation products for tungsten and lead targets bombarded by 1000-MeV protons is illustrated in Fig. 2. Note that high-energy fission produces symmetric fission products peaking in the range around $Z = 40$.

Fig. 2. Spallation product generation rate for 50-cm-diam 200-cm-long lead and tungsten targets bombarded on axis by 1000-MeV protons.

In The Radiation Damage To Materials

The type of radiation damage to materials at spallation neutron sources differs from that encountered at fission reactors in several respects. First, the evaporation phase of the spallation process produces enormous amounts of hydrogen and helium (one or two orders of magnitude more than at fusion reactors). Hydrogen can, for some materials such as zirconium, lead to the formation of metal hydrides; helium, at high operating temperatures, can form bubbles at grain boundaries and other defects which leads to material swelling and embrittlement. Second, the radiation field at a spallation source is much "harder" than the typical fission spectrum. Much remains to be learned about the effects of high-energy neutrons (and protons) on materials properties. Finally, the radiation field of a spallation source could have dramatic effects on the target coolant (e.g., light or heavy water) radiolysis that, in turn, could lead to radiation-enhanced corrosion problems.

COMPUTATIONAL TOOLS

LANL has world-class Monte-Carlo computational capability applicable to spallation-neutron source design; it also has the computer hardware and experienced people required to set up and run the codes and interpret the results. One part of the computational tool is based on the LANL version of the HETC Monte-Carlo code for the transport of nucleons, pions, and muons, which was originally developed at Oak Ridge National Laboratory (ORNL) [4]. Because of major modifications and additions made to the HETC code at LANL, this version of HETC has been renamed LAHET, and the system of codes based on LAHET is designated as the LAHET Code System (LCS) [5]. Below, we give a brief description of the breadth of capabilities that the LCS puts at the disposal of its users.

The LAHET Code System

The LCS (see Fig. 3) is a sophisticated code system based on several subcomponents, among which LAHET and MCNP are the major players. LAHET is a model-based Monte-Carlo code used for the transport and interaction of nucleons, pions, and muons at high energies (≤ 4 GeV). With the exception of measured nucleon-nucleon cross sections, LAHET uses nuclear models to describe particle interactions. LAHET uses the Bertini [6] or the ISABEL [7] model to describe the physics of the intranuclear cascade, and the Dresner evaporation model for the last phase of the nuclear interaction. The Fermi breakup model [8] replaces the Dresner model for describing the evaporation process for light nuclei. A pre-equilibrium model was recently added as an intermediate stage between the intranuclear phase and the evaporation phase. Two fission models (Rutherford-Appleton [9] and ORNL [10]) complement the set of physics models that LAHET uses.

The MCNP code [11] is a design-production code for low-energy neutron/photon/electron Monte-Carlo transport. The code is distributed and used internationally by nuclear system designers. The MCNP code is geared toward the transport of neutrons, photons, and electrons in matter. MCNP is a data-based code; it uses very detailed continuous-energy ENDF/B cross sections libraries for several hundred isotopes to describe the interaction of neutrons and photons with matter, down to sub-thermal energies. MCNP is a time-dependent Monte-Carlo transport code, capable of handling arbitrarily complex geometries.

Particle transport in both LAHET and MCNP is based on Monte-Carlo techniques. The philosophy used in the LAHET code is to treat all interactions by protons, pions, and muons within LAHET, but to treat neutron interactions only above a cutoff energy, typically 20 MeV. Any low-energy (< 20 MeV) neutron emerging from a reaction has its kinematic parameters recorded in a neutron file (NEUTP) for subsequent transport. For LAHET, a version of MCNP (called HMCNP) has been modified to accept the NEUTP file as an input source to complete the low-energy neutron transport. The low-energy transported neutrons can participate in nuclear reactions and produce additional neutrons and photons for transport within HMCNP.

Gamma-rays can also be transported by the LCS. During a LAHET calculation, a large quantity of information is recorded in a separate file, which another code (PHT—a photon source-generating code) can subsequently analyze to produce a gamma-ray source for HMCNP. The HMCNP phase of the calculation is then executed as a coupled neutron/photon transport problem. The photons produced in LAHET originate either from the decay of neutral pions produced in the intranuclear cascade phase or by the de-excitation of residual nuclei after the evaporation/high-energy fission phase. In a coupled neutron/photon problem, the neutron file NEUTP and the gamma-ray file GAMTP are merged (by the MRGNTP code in the LCS) to produce a combined neutron/photon file COMTP that describes the low-energy neutron source and high-energy-produced gamma-ray source for the entire system. HMCNP is then used to

transport these neutrons and photons plus gamma-rays produced from neutron-induced reactions below 20 MeV.

In addition, both LAHET and HMCNP can write history files (called HISTP and HISTX respectively), that contain a (nearly) complete description of events occurring during the computations. The code HTAPE (another code in the LCS suite of codes) is used to post-process the HISTP and HISTX files to extract a variety of information.

Fig. 3. LAHET Code System/CINDER'90 flow chart.

The CINDER'90 Code

CINDER'90 is a transmutation code used to follow the decay of nuclear species [12]. It uses nuclei production/destruction information from LAHET together with neutron fluxes from HMCNP to predict the time behavior of nuclear species through their production and subsequent decay. Each nuclide's concentration is determined by the history of gains from neutron-absorption reactions (spallation, fission, $[n,\gamma]$, $[n,2n]$, etc.) and radioactive decay of parent nuclides, as well as losses from its own decay and particle absorption. The total nuclide concentrations are obtained by summing partial concentrations. The CINDER'90 code uses a library of basic nuclear data to trace all possible transmutation paths, determining the partial concentration and associated activity of each nuclide as well as the integrated transmutation of each nuclide during a time increment. CINDER'90 accumulates nuclide concentrations and activities from nuclide properties as they are calculated. It then combines the post-processing data with decay and neutron-absorption data to obtain density (atoms/barn-cm and kg); activity (Ci/cm³ and Ci); decay power (W/cm³ and W); macroscopic neutron absorption (cm⁻¹); and decay spectra properties listed by nuclide, element Z, and mass A. The code also tabulates major contributors ($\geq 0.1\%$) to mass, activity, decay power, and macroscopic absorption. These results—activity inventory, decay power, macroscopic neutron absorption, etc.—have many practical applications. Some applications require the subsequent transport of the decay source in HMCNP to obtain a desired response, such as dose or dose-equivalent rates.

BARE-TARGET NEUTRONICS

Maximizing total low-energy neutron production, which depends on target material and geometry (as well as incident particle type and energy), is an important aspect of spallation-neutron-source target design—however, it is only part of the story. Once low-energy neutrons are produced inside the target, they must escape from the target before they can be moderated to energies that are *useful* in a variety of applications. Maximization of this leakage is another crucial aspect of target design. Target geometry and parasitic absorption in the target primarily control the leakage of low-energy neutrons. For example, for cylindrical targets, leakage from the front surface dominates total leakage at large target diameters (an undesirable effect). Parasitic neutron absorption in some spallation-target materials (such as tantalum and tungsten) is significant at large target diameters, whereas parasitic neutron absorption in lead is less important. Target neutronic performance is also a function of the energy and type of the incident particle, and of the target material and geometry.

Engineering realities (such as proton-beam windows, target canister material, target dilution by cooling material, and the profile and size of the incident particle beam) also affect the neutronic performance and design of a target; these practical matters must be explicitly dealt with in a realistic manner. The requirements of each particular application (e.g., source brightness vs. total leakage) also affect target design. In addition, the neutronic coupling/decoupling of a target with its immediate environment plays an important role in the overall performance of a spallation-target system. This is particularly true when coupling a spallation target to a neutron-amplifying blanket (as in plutonium disposition).

Target Geometry

As mentioned above, leakage maximization is a crucial aspect of spallation-neutron-source target design. Geometry and parasitic absorption of the target control the leakage of low-energy neutrons for a given target material. Figure 4 illustrates these effects, comparing low-energy neutron production and leakage for two typical spallation-neutron-source target materials—lead

Fig. 4. Low-energy neutron production and leakage as a function of target diameter for solid right-circular cylindrical targets bombarded on axis by 1-GeV protons. (a) A 30-cm-long tungsten target; (b) a 55-cm-long lead target.

and tungsten. The increased parasitic absorption in tungsten is significant at large target diameters, yet tungsten produces more low-energy neutrons than lead, especially at small target diameters. At large target diameters (infinite targets) lead and tungsten produce roughly the same number of low-energy neutrons. As can be seen in Fig. 4, leakage from the front surface of the targets dominates the total leakage at large target diameters.

Figure 4 also illustrates both the flexibility and complexity of designing spallation targets. For example, if target compactness and neutron leakage from the cylindrical surface are important, then one would choose a tungsten target with a diameter of approximately 10 cm. Indeed, this is the case for the LANSCE pulsed spallation-neutron-source application for materials science research [13]. On the other hand, if total neutron leakage alone dominates the target design criteria, one would choose a solid lead target with a diameter of about 100 cm. However, engineering realities concerning target structural support and target cooling must be addressed; these criteria have a tremendous impact on spallation-target design.

Energy- and Material-Dependent Effects

In addition to geometry (size and shape), the neutron production and leakage from a spallation target depends on the target material and on the energy and type of the incident particle. Figure 5 shows the dependence of low-energy net neutron production—spallation plus (n,xn) and fission neutrons—on the energy of the incident proton and the target material. As can be seen in Fig. 5, fissionable targets produce more low-energy neutrons, but at a cost of more energy deposition in the target material. As mentioned before, neutron leakage (and not neutron production) is a better measure of target performance. Note (in Fig. 4) that neutron leakage from a solid lead target is much better than that from a solid tungsten target. Depending on the application, there are ways of mitigating this effect by employing the split-composite target idea [14].

Fig. 5. Production of low-energy neutrons as a function of incident proton energy for various target materials. The targets are 50-cm-diam $\times$ 200-cm-long right-circular cylinders; the protons are incident on the cylindrical axis.

THE SPLIT-COMPOSITE TARGET CONCEPT

As discussed above, target geometry and parasitic absorption in the target primarily control leakage of low-energy neutrons from the target. The increased parasitic absorption in tungsten is significant at large target diameters. For tungsten (and any other neutron absorbing targets, such as tantalum), the detrimental parasitic absorption effect is decreased by splitting the target in the direction of the incident charged particle beam. This technique also helps mitigate excessive neutron leakage from the front surface of the target (by making the target neutronically reentrant). Splitting a target increases low-energy neutron leakage thereby reducing parasitic neutron absorption. However, low-energy neutron production is also degraded because secondary high-energy particles also escape from the central target zone. This loss in neutron production is diminished by employing a radially-composite target consisting of a central region and a radial zone. Depending on the application of the split-composite target concept, it may also be desirable to have a target both axially- and radially-composite as well as split. These target concepts are illustrated in Fig. 6.

The split-composite target concept has three unique features. *First* the split-composite target is neutronically reentrant: the central target zone is split axially (by flux traps) and the neutron production is spatially distributed deeper along the target axis. The term *flux trap* refers to the spaces between the target segments of a split target. Neutron leakage is reduced from the front target surface, allowing the use of large target diameters at reduced power densities without large front-surface leakage losses. *Second* splitting a target increases low-energy neutron leakage and reduces parasitic neutron absorption. The central target zone of a split-composite

Fig. 6. Basic target concepts.

target provides *geometric decoupling* between the various regions in the central target; the axial splitting of the central target zone accomplishes this geometric effect. Geometric decoupling also enhances leakage of high-energy secondary particles into the radial/lateral target zone to cause spallation reactions. Production of low-energy spallation neutrons in the radial/lateral target zone increases their chance to escape (leak) from the split-composite target. *Third* a split-composite target allows for the possibility of using *neutronic decoupling*—employing neutron-absorbing material in and between target regions to reduce parasitic neutron absorption in the various target zones, and neutronicly isolating target zones from each other and their surroundings. (The Los Alamos ^3He APT target system is an ideal application of the neutronic decoupling concept [14].)

The split-composite target concept also allows the use of high-temperature materials (such as tungsten) in the central target zone. Lead can be used in the radial or lateral target zone to enhance neutron production and utilization.

Figure 7 quantitatively shows the effects of splitting a target and making the target both split and radially composite. Note that splitting the target increases neutron leakage for flux-trap gaps that are ≥ 5 cm, decreases front-surface neutron leakage, but also decreases neutron production (as the flux-trap gaps increase). Making the target both split and radially composite enhances both the total low-energy neutron leakage and production. Split target and split-composite target concepts have been applied to projects as varied as pulsed spallation neutron source design [13]; Accelerator Production of Tritium (APT) [14], Accelerator Transmutation of Waste (ATW) [15], and are being studied for quasi-continuous and continuous spallation neutron source applications. Since splitting of the target distributes the neutron source over a larger volume, the split-composite target concept is more readily suited to applications where total neutron leakage, rather than peak flux, is the overriding design criterion.

Fig. 7. Low-energy neutron production and leakage as a function of flux-trap gap for a split target and a split, radially-composite target. Both targets have twelve 2.5-cm-thick tungsten plates in the central target zone. For the zero-flux-trap-gap case, the targets are solid. The split target has 50-cm-diam plates, whereas the split, radially-composite target has 20-cm-diam plates surrounded by a 15-cm-thick lead annulus for a total diameter of 50 cm. The 1-GeV proton beam is incident on the target axes.

LIQUID TARGETS

For applications where high neutron flux is an important figure of merit, spallation targets must be compact and capable of handling high power densities. For such applications, liquid metal targets hold some promise. The main advantages of liquid targets are: a) high target mass density; b) high heat removal capability; c) reduced radiation damage; and d) no cooling water in the proton beam. The main disadvantage is how to contain the liquid target; however, this problem is under active study. The main liquid target materials under consideration are lead, lead-bismuth, and mercury. Polonium production from bismuth is a potential safety concern for a lead-bismuth target.

CONCLUSIONS

Because of recent advances in high-power accelerator technology, spallation is becoming an important alternative method to fission for producing high fluxes of neutrons for a variety of applications. Liquid targets will become important when high power density and heat removal dominate spallation target design. The low parasitic neutron absorption in liquid lead is an

important attribute for such applications as plutonium disposition and continuous (reactor-like) neutron sources. Mercury is being considered for pulsed neutron sources where parasitic neutron absorption is not such a critical factor [16]. As mentioned above, tantalum, tungsten, lead, and depleted uranium have found applications in the areas of pulsed and continuous spallation neutron sources, and tungsten and lead are being considered as target materials for accelerator-based production of tritium.

ACKNOWLEDGMENTS

We acknowledge useful discussions with Phillip Ferguson. This work is supported by the United States Department of Energy under contract W-7405-ENG-36 to the University of California.

REFERENCES

- [1] Rutherford, E., "Collisions of α Particles with Light Atoms. IV. An Anomalous Effect in Nitrogen," *Phil. Mag.*, **37**, 581, January-June 1919.
- [2] Lawrence, E. O. and Edlefsen, N. E., "On the Production of High Speed Protons," *Science*, **LXXII**, NO. 1867, 376, October 10, 1930.
- [3] Livingston, M. S., LAMPF, a Nuclear Physics Research Facility, Los Alamos National Laboratory report, LA-6878-MS (1977).
- [4] Radiation Shielding Information Center, "HETC Monte Carlo High-Energy Nucleon-Meson Transport Code," Oak Ridge National Laboratory report CCC-178 (August 1977).
- [5] Prael, R. E. and Lichtenstein, H., "User Guide to LCS: The LAHET Code System," Los Alamos National Laboratory report LA-UR-89-3014 (September 1989).
- [6] Bertini, H. W., *Phys. Rev.* **188**, 1711 (1969).
- [7] Yariv, Y., and Fraenkel, Z., *Phys. Rev.* **166**, 2227 (1979).
- [8] Brenner, D. J., Prael, R. E., Dicello, J. F., Zaider, M., "Improved Calculations of Energy Deposition from Fast Neutrons," in *Proceedings Fourth Symposium on Neutron Dosimetry*, EUR-7448, Munich-Nuremberg (1981).
- [9] Atchison, F., "Spallation and Fission in Heavy Metal Nuclei under Medium Energy Proton Bombardment," in *Targets for Neutron Beam Spallation Sources*, Jül-Conf-34, Kernforschungsanlage Jülich GmbH (January 1980).
- [10] Barish, J., et al., "HETFIS High-Energy Nucleon-Meson Transport Code with Fission," Oak Ridge National Laboratory report ORNL/TM-7882 (1981).
- [11] Briesmeister, J., editor, "MCNP—A General Monte-Carlo N-Particle Transport Code—Version 4A," Los Alamos National Laboratory report LA-12625 (1993).
- [12] Wilson, W. B., et al., "Accelerator Transmutation Studies at Los Alamos with LAHET, MCNP, and CINDER'90," in *Proceedings of the Workshop on Simulating Accelerator Radiation Environments*, Los Alamos National Laboratory report LA-12835-C (October 1994), pp. 115-133.
- [13] Russell, G. J., Bowman, C. D., Whitaker, E. R., Robinson, H., and Meier, M. M., "LANSCE High-Power (200 uA) Target-Moderator-Reflector-Shield," in *ICANS-VIII: Proceedings of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources*, Rutherford-Appleton Laboratory report RAL-85-110 (November 1985), pp. 272-293.
- [14] Russell, G. J., Pitcher, E. J., and Daemen, L. L., "Split-Composite Spallation Neutron Source Targets and Accelerator Production of Tritium," *Trans. Am. Nucl. Soc.*, **69**, ISSN: 0003-018X, 440-441 (1993).
- [15] Daemen, L. L., Pitcher, E. J., and Russell, G. J., "Technetium-99 Burner for the Hanford Waste," *Trans. Am. Nucl. Soc.*, **69**, ISSN: 0003-018X, 429-431 (1993).
- [16] Bauer, G., private communication.