Nuclear Data Needs for Accelerator-Driven Transmutation System

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Abstract

The possibilities of several new technologies based on use of intense, medium-energy proton accelerators are being investigated at Los Alamos National Laboratory. The potential new areas include destruction of long-lived components of nuclear waste, plutonium burning, energy production, and production of tritium. The design, assessment, and safety analysis of potential facilities involves the understanding of complex combinations of nuclear processes, which in turn places new requirements on nuclear data that transcend the traditional needs of the fission and fusion reactor communities. In this paper an assessment of the nuclear data needs for systems currently being considered in the Los Alamos Accelerator-Driven Transmutation Technologies program is given.

I. Introduction

Recent progress in high-power accelerator technology, materials separations, and neutron sources has enabled new accelerator-based systems that can impact important problem areas. Several such systems are currently being investigated in the Accelerator-Driven Transmutation Technology (ADTT) program at Los Alamos. These include tritium production, plutonium disposition, destruction of long-lived components of nuclear waste, and ultimately long-term energy supply requirements. The systems discussed here utilize a number of common components and features -- specifically a high-power accelerator, a target which serves as a neutron source, a blanket region where materials undergo nuclear interactions, and separations processes which recover by-products and introduce new materials for feed.

Comprehensive reviews have been written by Koning on the availability of high energy nuclear data and model codes for accelerator transmutation of waste (ATW) problems[1] and on the requirements for evaluated data for such problems.[2] In the present paper we specialize our considerations to ADTT systems being studied at Los Alamos National Laboratory. In general, our findings are consistent with and complementary to Koning's, except some new materials are introduced here. Additionally, some materials that Koning includes are omitted in our review, but we should emphasize that in this brief summary we have focused on our most important data needs and have not been as comprehensive as Koning. Lastly, we also consider some of the more important neutron data needs at lower energies, whereas Koning concentrates on the region above $E_n = 20$ MeV.

In Section II we outline the ATW concept, in Section III we describe the major components of ATW, and in Section IV we summarize the general requirements for nuclear data needs for the various potential technologies. In Section V we discuss a calculational scheme used at Los Alamos to analyze ADTT systems and outline the associated needs for evaluated (or calculated) nuclear data. We assess the implications of ADTT programs on experimental data needs in Section VI and summarize some experimental activities being carried out at Los Alamos. Finally, we give a summary of our conclusions in Section VII.

II. The Accelerator Transmutation of Waste Concept

Figure 1 provides a schematic representation of major components of ATW systems. An accelerator, based upon technology advances resulting from the SDI program, produces a medium energy (~ 1000 MeV) beam of protons which stop in a heavy metal target. The interaction of the beam with the target produces a copious source of neutrons which is then multiplied in intensity in the blanket region that surrounds the target. This blanket also serves to slow the neutrons down to low energies where probabilities for transmutation reactions are large. Materials such as plutonium, waste actinides, or long-lived fission products are introduced continuously into this intense neutron field via liquid carriers The fluid carrier used in the ATW concepts is a molten fluoride salt, demonstrated in the Oak Ridge Molten Salt Reactor program of the 1960's and 1970's. Transmutation or destruction reactions occur on long-lived radionuclides which produce shorter-lived or non-radioactive by-products. In the ATW system material separations are used to remove by-products for subsequent reintroduction into the system. Resulting discharge streams can potentially be managed in storage environments for periods of several centuries or disposed of directly as low-level waste.

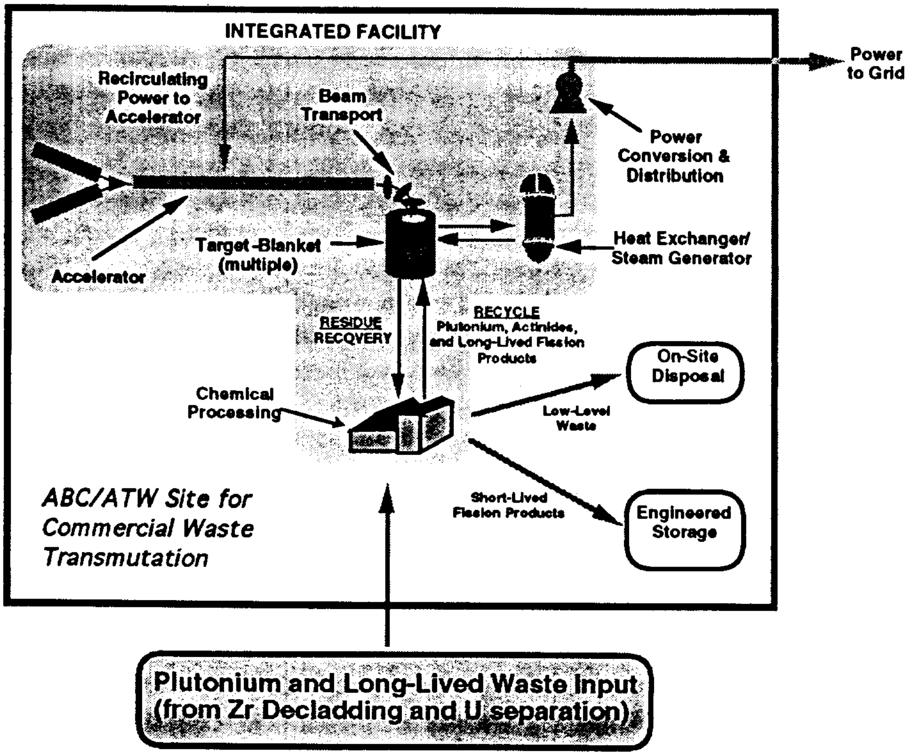


Fig. 1. Overview of the components of the ATW system.

The process of destroying large amounts of plutonium or other actinides in this system produces large amounts of thermal power (just as in a power reactor). This power is converted into electric power, a fraction of which is diverted to run the system's accelerator. Approximately 85 percent of the electric power produced in the system is then available for supply to the commercial grid. An appropriately designed ATW system can destroy all major types of long-lived radionuclides, both fission product and actinide species resident in high-level, spent-fuel waste. Long-lived radionuclides include plutonium, neptunium, and curium and a relatively small number of fission products. These include ^{99}Tc, ^{129}I, ^{135}Cs, ^{107}Pd, ^{93}Zr, ^{126}Sn, and ^{79}Se.

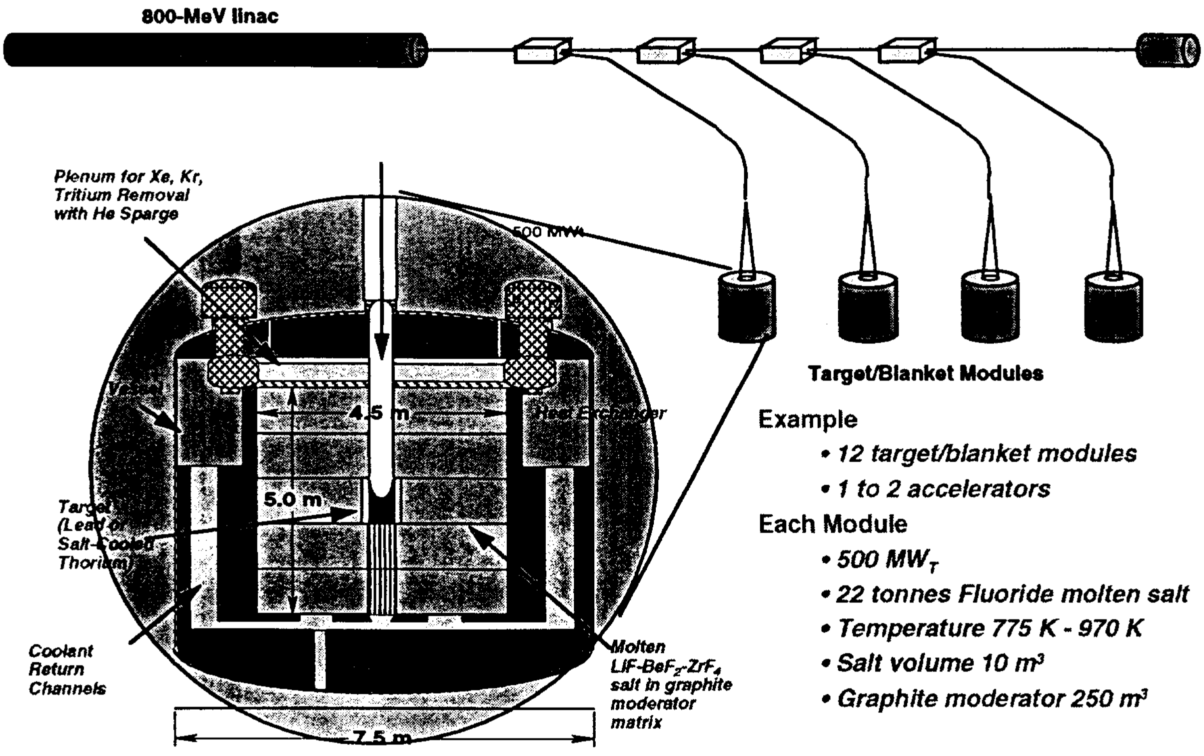
These two classes of long-lived radionuclides present separate challenges to repository designers worldwide. The long-lived actinides contribute principally to radiotoxicity associated with high-level nuclear waste and to possible future proliferation impacts. Fission products such as ^{99}Tc and ^{129}I contribute to the long-term cumulative risk resulting from a repository because of their relatively larger chemical mobility.

The accelerator system of ATW provides a source of neutrons which can transmute fission products while simultaneously destroying actinides. In doing so, ATW reduces significantly or effectively eliminates the risk sources associated with long-term disposal. The specific choice of design of the ATW concept -- use of fluid fuel carriers -- allows creation of high-neutron flux systems which operate in a neutron energy regions where nuclear cross sections are large. This leads to smaller inventories of materials needed in the system to sustain a desired transmutation rate. This low-inventory feature, in turn, has an important overall system impact in that times required to significantly reduce long-lived radioactive materials to very low levels are much less than for other nuclear concepts. Finally the accelerator allows subcritical operation where macroscopic nuclear multiplication stops when the accelerator beam is turned off. This adds an important new element of control into the ATW nuclear system.

III. Major Components of ATW

A linear accelerator used to produce a high-current beam of protons at energies around 1000 MeV. It is essentially a high-current version of the Los Alamos Meson Physics Facility (LAMPF) accelerator that incorporates advances made under the Strategic Defense Initiative Neutral Particle Beam Program. These advances are related to the low-energy end of the accelerator and involve devices such as the radiofrequency quadrupole (RFQ) which provide dramatic improvements in the creation and initial acceleration of high-current beams.

The next major component of these system is the target/blanket shown in Figure 2. As shown, the proton beam enters the configuration from the top where it strikes a heavy metal neutron production target. An attractive material for this target is lead, from which production of thirty neutrons can occur per incident 1000 MeV proton. Surrounding this target is a blanket region consisting of a graphite moderator and passages for a liquid fuel which contains materials to be transmuted or destroyed. The blanket operates in a subcritical mode with multiplication of source neutrons by a factor of twenty to twenty-five. This liquid fuel is a molten fluoride salt which provides attractive operational features compared with more conventional solid fuel elements. The fluid form allows high neutron economy to be maintained in the blanket by allowing neutron absorbers to be removed. A significant fraction of such products can be removed by on-line methods such as sparging and electrolysis. This feature allows achievement of burnup levels during operation that are significantly higher than those possible in specially designed solid-fueled reactor systems. The fluid form also adds performance enhancements related to high temperature, low-pressure operation which can lead



Example
- *12 target/blanket modules*
- *1 to 2 accelerators*

Each Module
- *500 MW$_T$*
- *22 tonnes Fluoride molten salt*
- *Temperature 775 K - 970 K*
- *Salt volume 10 m^3*
- *Graphite moderator 250 m^3*

Fig. 2. A conceptual layout for the ATW target/blanket configuration.

to thermal-to-electric conversion efficiencies greater than forty percent. Finally the fluid fuel provides safety enhancements related to inherent reactivity control and improved means for passive cooling of the blanket assembly.

As presently envisioned, such a target/blanket module would operate at a thermal power level of 500 MW. The module size lends itself to attractive features associated with passive cooling and a number can be used as "building blocks" to make up a system which would operate at a total desired thermal power. Anywhere from four to six such modules could be driven by an accelerator operating at a current less than 100 milliamperes. Such a system could support the long-lived radionuclide discharge from up to six 3000 MW$_T$ light-water reactors.

The final component of ATW systems is that related to separations. These are shown schematically in Figure 3. Methods such as chopping and leaching followed by precipitation or fluoride volatility could be used to prepare the spent fuel feed for ATW by removing uranium and the cladding material. The resulting stream consisting of actinides and fission products would enter the ATW separations system. There methods such as precipitation, electrolysis, distillation, and centrifugation would recover the actinides and key long-lived fission products for destruction through transmutation. These products must be recycled within the system's blanket neutron field to achieve very high-levels of destruction. The separations include the necessary components to achieve needed product removal for recycle as well as removal of products that interfere with the system's operation. The final separations step involves back-end processes to "polish" discharge streams so

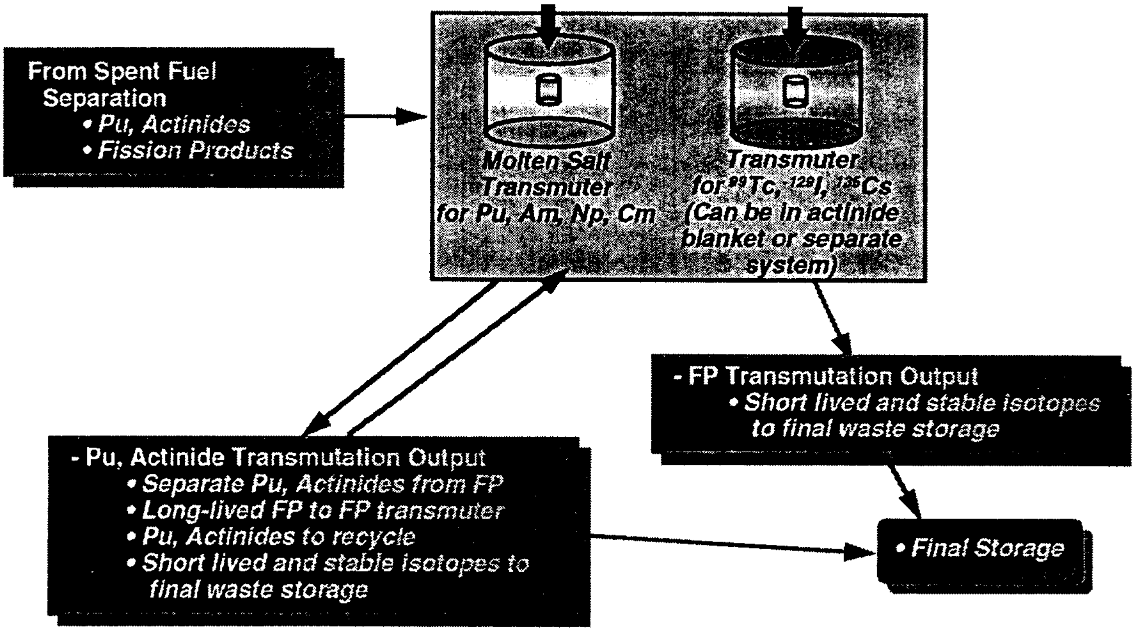


Fig. 3. Overview of the separations associated with an ATW system.

that radioactive material concentrations in them can be reduced to very low levels. The resulting product would be suitable for low-level waste disposal. The separations system also removes the bulk (approximately ninety five percent) of products created during fission which have half-lives less than thirty years. This high-level waste discharge stream would be sent to engineered storage facilities where cooling for periods of several hundred years would reduce emitted radiation to essentially negligible levels.

IV. General Requirements for Nuclear Data

In each of the Los Alamos ADTT concepts, there is a target region where materials (target, target cladding, breeding material, etc.) are exposed to direct beam protons and secondary neutrons ranging in energy from the primary beam energy down to thermal energies. Surrounding the target area are salt fuel materials, blanket and moderator materials, coolants, and structural materials that are not exposed to the direct proton beam but which are irradiated by a high flux of neutrons ranging from a very hard spectrum with a significant number of medium-energy neutrons, to an intermediate energy neutron spectrum , and finally to essentially a thermal neutron spectrum.

For all materials present in significant quantities in the target and surrounding region, neutron-induced data adequate for neutron transport calculations are required. These data are needed to calculate the energy distributions of down-scattered neutrons that drive the transmutation reactions in the blanket/moderator regions and, perhaps equally or even more demanding, that can be used in shielding calculations for these complex, medium-energy neutron systems. Additionally, individual nuclide production or spallation yields are required, together with information on recoil nuclei energy distributions that can be used to obtain DPA and damage cross sections up to high energies for structural materials. Lastly, transmutation and activation cross sections are necessary for neutron-induced reactions, including cross sections for formation of isomeric states. In terms of nuclear reactions, the data required are neutron total, elastic and inelastic scattering, double differential (n,xn) and (n,xp), (n,γ), (n,f), (n,x), and (n,xγ) cross sections, plus production cross sections for individual nuclides as functions of Z and A with isomeric state production included.

For actual target materials, that is, materials that are exposed to the direct proton beam, essentially the same data requirements exist for proton-induced reactions as described above for neutron-induced reactions. Most importantly, (p,xn), (p,xp), (n,xn), and (n,xp) production cross sections are required as functions of incident energy and emission angle and energy for all materials directly exposed to the particle beam. Spallation product yields are needed, as well as recoil nuclei energy distributions that can be used to obtain damage cross sections up to high energies for solid target materials. Information on isomer production must be provided, and (p,xγ) and (n,xγ) yield data are needed for shielding calculations. Proton-induced data would also be useful for materials that are not directly exposed to the proton beam, but these data are of lower priority than the incident neutron data.

Target materials under current (or recent) consideration in Los Alamos designs are W, Pb, Th, and U. These elements, plus the hastelloy and zircalloy target cladding (Cr, Fe, Ni, Zr, Mo, Sn), a breeding material (^{3}He), and heavy water (^{2}H, O), are exposed to both the direct proton beam and high-energy neutrons from (p,xn) reactions, depending on the particular ADTT concept. The remaining materials in and around the target region, including the molten salt fuel carrier materials (Li, F, Be, Zr), structural materials (C, Al, Si, P, Cr, Fe, Mn, Ni, Zr, Mo, Sn), salt coolant (Na, B), and blanket/moderator materials (^{1,2}H,Be, C, O), are irradiated by neutrons from (p,xn) reactions, with a significant hard component near the target and becoming a moderated fission spectrum further into the blanket region. Additionally, significant amounts of reactor fission-product and actinide waste are loaded into the ATW blanket region, plus ^{239}Pu in the case of the plutonium-burning application. Important higher actinides are ^{232,233}Pa (for the ^{232}Th - ^{233}U fuel cycle), ^{237,238}Np, $^{241-244,242m,244m}$Am, and $^{242-248}$Cm.

Transmutation/activation cross sections and decay data are required for all nuclides that are products of spallation, fission, absorption, activation, (n,x), (n,xn), etc., reactions, including nuclides that are formed in isomeric states. The magnitude of this requirement is better envisioned from Fig. 4, in which the range in neutron and proton number of spallation products formed by 800-MeV proton reactions on a tungsten target is superimposed on the Chart of the Nuclides. The N,Z distribution of fission products from thermal neutron fission of ^{235}U is also included in the display. Obviously, there is a good deal of overlap between the fission and spallation product ranges, except that the latter cover a much broader range in Z and N. Fission products are more important than spallation products in the concepts that include actinides, although both types of data are required for all concepts.

The list of materials requiring transmutation/activation/decay data is obviously quite extensive and is the reason that massive (>10000 reactions) data libraries are under development.[3] This is further illustrated by Fig. 5, which shows the distribution of spallation products as a function of product mass from1-GeV proton bombardment of Pb. From the distribution in Fig. 5 we surmise that transmutation data for spallation and fission products should roughly cover the mass range$10 \leq A \leq A_{target} + 2$, with the mass range from the target down to $A_{target} - 20$ clearly being the most important region. A list of the more important long-lived fission products that are transmutation candidates is given in Table 1, together with summary information on low energy cross sections from the compilation of Mughabghab.[4]

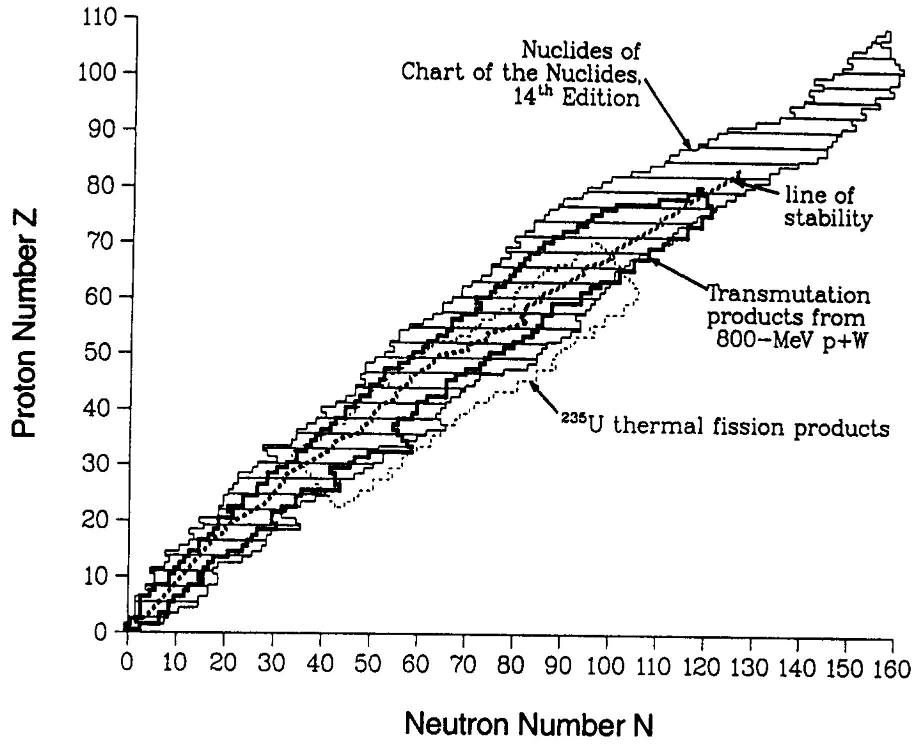


Fig. 4. Range in Z and N of spallation products from 800-MeV proton bombardment of tungsten.

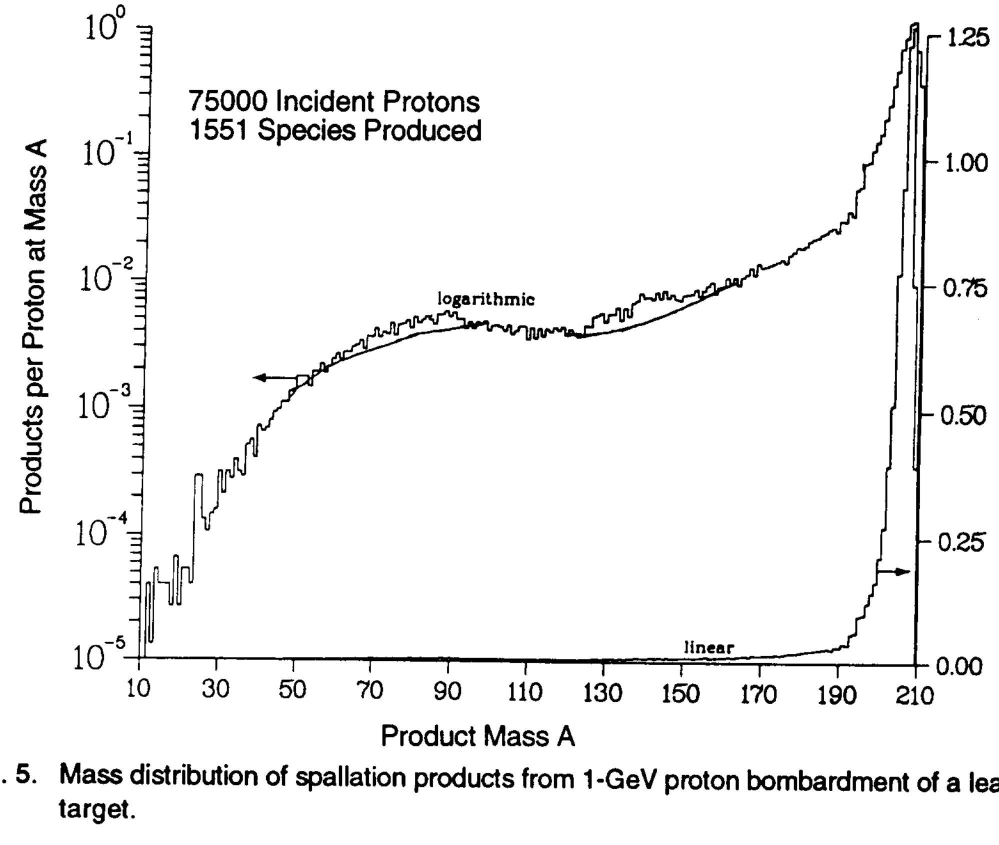


Fig. 5. Mass distribution of spallation products from 1-GeV proton bombardment of a lead target.

Table 1. Long-lived fission product transmutation candidates. The cross sections are from Mughabghab[4] and the resonance parameter comment refers to ENDF/B-VI.

Nuclide	Half Life (Years)	Thermal Capture Cross Section (b)	Resonance Integral (b)	Resonance Parameters
^{79}Se	6.5×10^4	(10)?	-	No
^{93}Zr	1.5×10^6	2.5 ± 1.5	-	~ No
^{99}Tc	2.1×10^5	20. ± 1.	340 ± 20	Yes
^{107}Pd	6.5×10^6	1.8 ± 0.2	86.6^c	Yes
^{126}Sn	1.0×10^5	(0.14)?	-	No
^{129}I	1.6×10^7	27. ± 3.	36 ± 4	Yes
^{135}Cs	3.0×10^6	8.7 ± 0.5	62 ± 2	No

Regarding transmutation data for actinides, data are required for nuclides important in the ^{232}Th - ^{233}U energy-production cycle and in burning ^{239}Pu, as well as the higher actinides in fission reactor waste that would be introduced into an ATW system for destruction, as detailed above. Considering all the actinides that must be included in analyses of these systems, the list is truly extensive but fortunately reasonable evaluated data exist for many of them from the fission reactor program, at least up to incident neutron energies of 20 MeV. A qualitative assessment of evaluated data in the ENDF/B-VI file for important higher actinides is given in Table 2, including thermal cross sections from Mughabghab's compilation.[4] Note that there are presently no evaluations in the ENDF/B-VI file for ^{232}Pa, ^{244}Cm, or ^{244m}Cm, and that the evaluations for ^{238}Np, ^{242}Am, ^{242}Cm, and ^{247}Cm are regarded as "weak."

V. Neutronics Calculational Scheme and Evaluated Data Requirements

Design and feasibility studies for ADTT systems obviously require detailed transport calculations of radiation associated with the stopping of protons of energy 1.0 GeV in various target materials. As outlined above, such calculations require information on nuclear interactions by protons and neutrons from essentially zero energy up to the primary beam energy with target materials, coolants, cladding and structural materials, moderator and blanket materials, fission and spallation products, and actinides. Such transport calculations are currently done at Los Alamos in the following manner: (1) the LAHET Monte Carlo transport code[5] tracks neutrons from the highest energy down to a lower energy cutoff of 20 MeV, using on-line nuclear models to calculate cross sections; (2) all neutrons born or scattered below 20 MeV are recorded as source particles for subsequent Monte Carlo transport calculations with the high energy version of the general Monte Carlo code HMCNP,[6] using tested cross section libraries from the national evaluated data file, ENDF/B-5; (3) reaction products and fluxes are tallied and passed on to a separate code, CINDER-90,[7] for transmutation calculations, utilizing a massive activation cross section and decay data library. This calculational path is outlined in more detail in Fig. 6.

The above procedure is satisfactory for scoping calculations. It is well known, however, that the nuclear physics in the LAHET code is most applicable for particles in the medium energy range, whereas using the on-line nuclear models down to 20 MeV is not appropriate, most especially for lighter elements. As a result, a significant and unnecessary component of error is introduced in such calculations, and it affects subsequent calculations that utilize neutron fluxes from LAHET/HMCNP

Table 2. Higher actinide transmutation candidates.

Nuclide	Half Life	Thermal $\sigma_{n,g}$ (b)	Thermal $\sigma_{n,f}$ (b)	ENDF/B-VI Quality
^{237}Np	2.1 x 10^6 y	176 ± 3	21.5 ± 2.4	Good
^{241}Am	433 y	587 ± 12	3.2 ± 0.1	Reasonable
^{243}Am	7370 y	75.1 ± 1.8	0.198 ± 0.004	Need Update
^{242}Cm	163 d	16 ± 5	< 5	Very Weak
^{244}Cm	18 y	15.2 ± 1.2	1.04 ± 0.20	Reasonable
^{246}Cm	470 y	1.22 ± 0.16	0.14 ± 0.05	Need Update
^{247}Cm	1.6 x 10^7 y	57 ± 10	81.9 ± 4.4	Weak
^{248}Cm	3.5 x 10^5 y	2.63 ± 0.26	0.37 ± 0.05	Need Update
		MOST SERIOUS DATA PROBLEMS		
^{232}Pa	1.3 d	700 ± 100	464 ± 95	None
^{238}Np	2.1 d	~ 300	2088 ± 30	Very Weak
^{242}Am	16.1 h	?	2100 ± 200	Very Weak

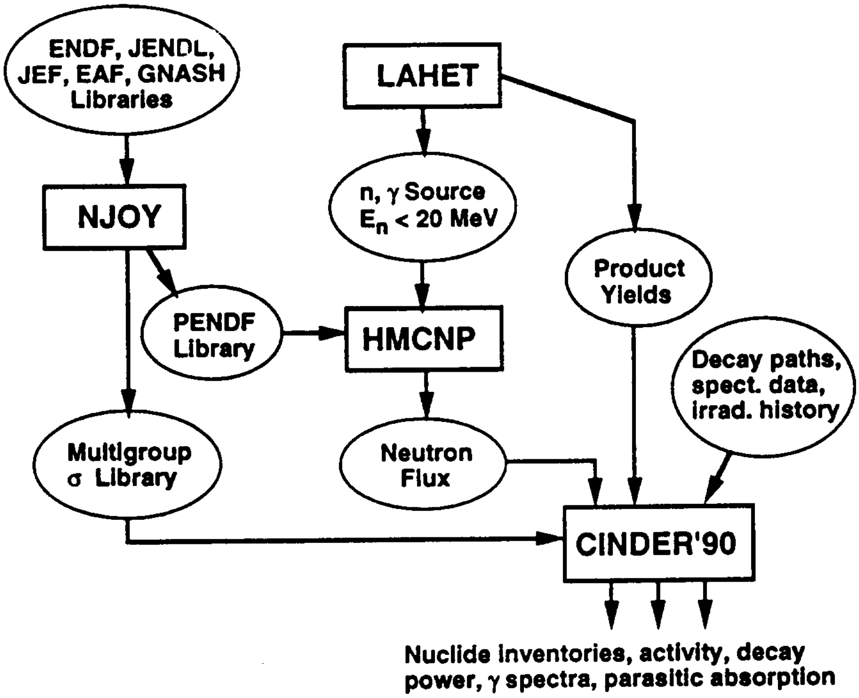


Fig. 6. Simplified calculational path used in neutronics analyses of ADTT systems.

analyses, e.g., radiation damage, transmutation, nuclide inventories, engineering design, shielding, and safety calculations.

A straightforward solution to circumvent this problem is to extend the validated neutron transport data library (now ENDF/B-V) from the current energy limit of 20 MeV to a more appropriate higher energy where the models in LAHET are expected to be more reliable. This extension could be accomplished utilizing experimental data, systematics, and nuclear theory. An upper energy limit in the range 100 - 200 MeV appears feasible and adequate for the purpose.

To summarize, the two nuclear data libraries of major importance to the ADTT projects are the neutron transport library and the transmutation/activation/decay data library. Efforts have been directed at developing a transmutation/activation/decay data library[3] and, while such libraries still need significant improvement, considerable progress has been made. For neutron transport, however, an adequate data library with enough materials to be useful only exists to 20 MeV.

The third nuclear data component that is crucial in analyses performed at Los Alamos is the LAHET code[5] and the intranuclear cascade/preequilibrium/evaporation modeling that is built into the code. The LAHET code is discussed in a paper by Prael[8] at this meeting and will not be described here. Significant efforts have been directed at validating and improving the double-differential proton-induced neutron emission spectra calculated with the code,[9,10] by comparing calculations with both thin and thick targets.[11,12] A n example is shown in Fig. 7, where the thick-target neutron yield measured[11] with 113-MeV protons on Al is compared to LAHET calculations.[10]

A problem area that still needs improvement deals with the calculation of distributions of spallation products. Recent measurements by Ullmann et al.[13] of mass yields from 800-MeV proton bombardment of W are compared with LAHET calculations in Fig. 8. It is found that approximately 52% and 38% of the calculated mass yields disagreed with the two measurements presented by a factor of 2 or greater.

A second feature in LAHET calculations of spallation yields that should be addressed concerns the fact that all product nuclei are created in their ground states. Isomers are known to be present in fission products, and we have observed significant isomeric state branching as well in calculations of spallation reactions with the GNASH code.[14] For example, branching ratios are shown in Fig. 9 for several Pb isomers calculated for neutron reactions on ^{208}Pb at incident energies up to 150 MeV. The branching ratios tend to increase rapidly with incident neutron energy near their thresholds but then flatten out at higher energies. Because the branching ratios are so large (between 0.4 and 0.8 at higher energies), we feel that these effects should be included in the spallation calculations that are used in design studies.

VI. Experimental Data Needs for ADTT Programs

In his review, Koning[1] finds that while there are a number of experimental results available in the 20 - 1500 MeV energy range, there are still many gaps in data and a careful study is required to properly assess the overall experimental data needs. We have not made such a study, but we have identified a number of shortcomings in data, both at medium and at low energies, which need to be addressed for ADTT purposes. In a general sense, our viewpoint is that the most important experimental needs are those which impact the three major evaluation components listed in Section V. In this context some general comments can be made:

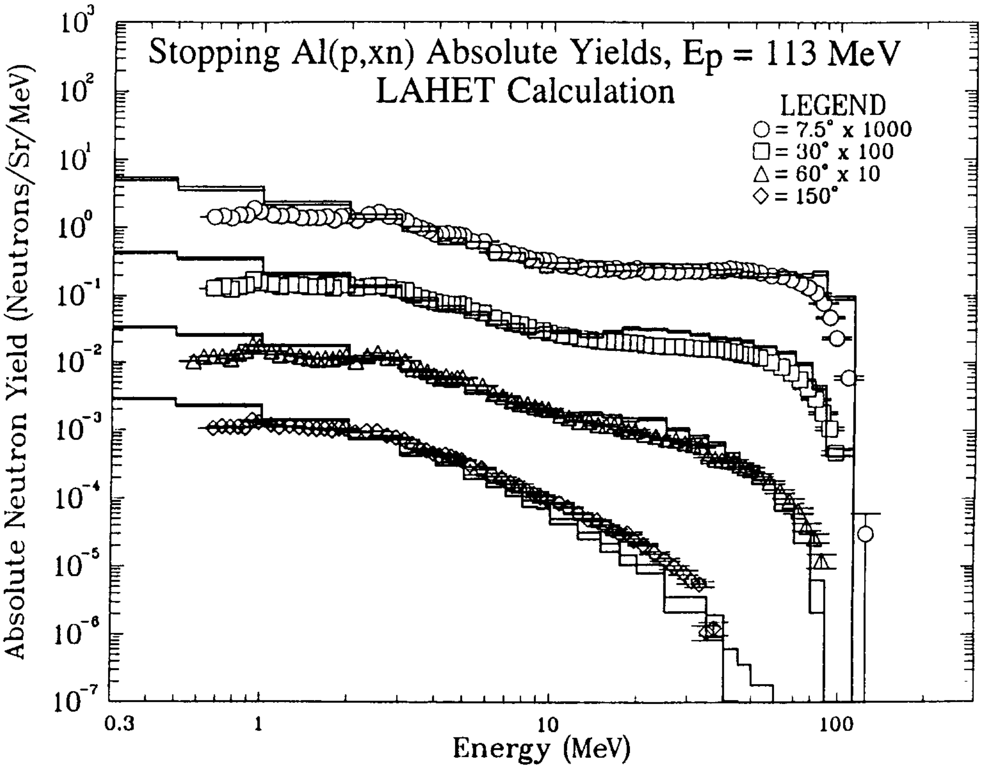


Fig. 7. Comparison of LAHET calculations[10] with measured[11] thick-target yields at several angles from Al(p,xn) reactions with 113-MeV protons.

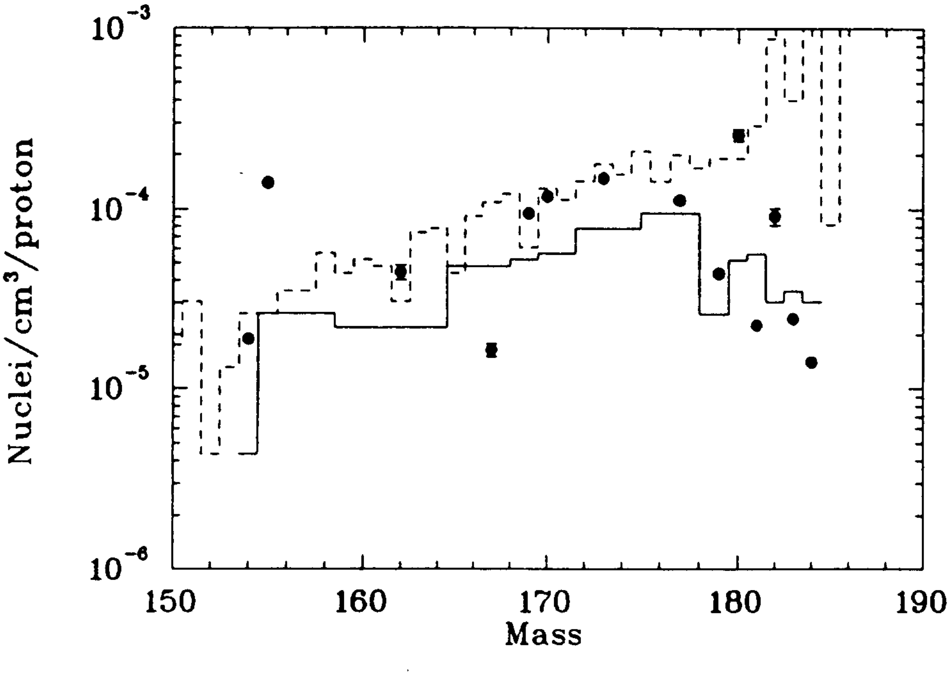


Fig. 8. Comparison of measured and calculated (LAHET) summed mass yields for 800-MeV protons on natural W.[13] The dashed line indicates calculated yield summed over all nuclei at the given mass; the solid line is the calculated sum over only those nuclei that were observed. The solid line should be compared to the data (solid circles).

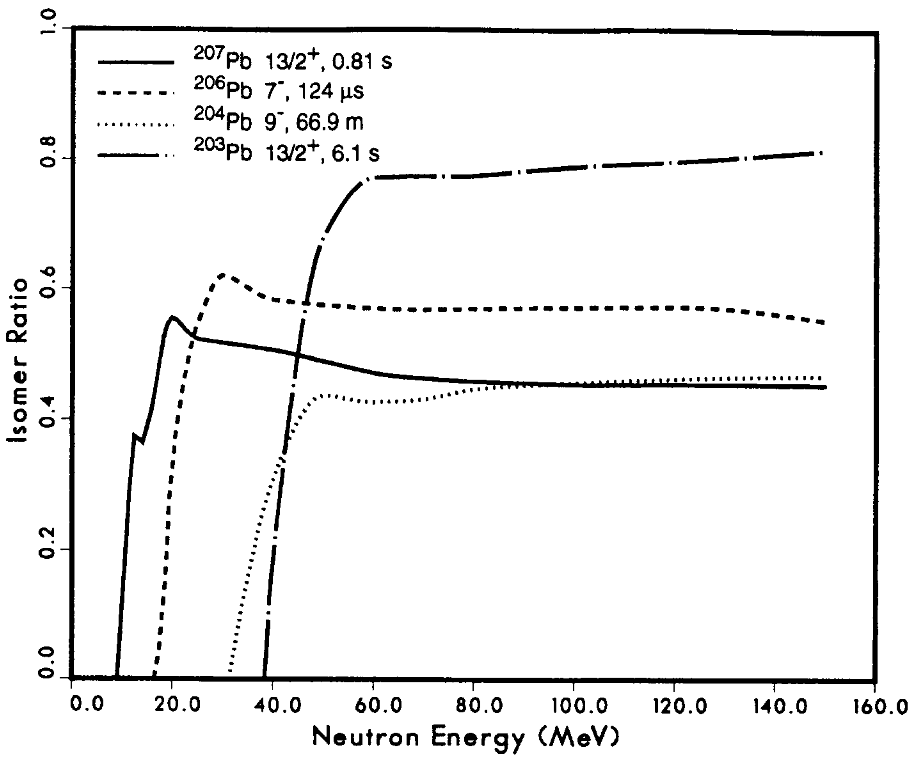


Fig. 9. Isomer ratios calculated with the GNASH code for four isomeric states in Pb isotopes formed by neutron reactions with ^{208}Pb.

- Transport Data Library. Nuclear theory codes will play a large role in developing the required transport data libraries. Experiments that measure proton and, especially, neutron emission spectra as functions of angle for appropriate target nuclei bombarded by protons or neutrons are very useful in testing calculations with codes such as FKK-GNASH[15] and LAHET[5]. Similarly, measurements that identify specific product nuclides, either directly or indirectly through, for example, (n,xγ) reactions, are very useful for testing nuclear model codes. Additionally, a very important component for performing theoretical calculations with codes like FKK-GNASH is a reliable optical model potential. While good nucleon potentials exist at lower energies, the same is not true for higher energies, and nucleon-nucleus potentials of a global nature that are reliable up to and including medium energies are required. Experimental data are needed that would support determination of such potentials such as measurements of neutron total cross sections, neutron and proton reaction cross sections, and differential elastic and inelastic neutron and proton scattering cross sections.

- Transmutation/Activation/Decay Data Library. A great deal of the cross section data in these libraries must, of necessity, be calculated. To support such calculations, there is a significant body of experimental data from the fission and fusion reactor programs, and a significant library validation effort using accumulated reaction cross section data has been undertaken by Muir and Wilson.[16] However, experimental data are sparse or discrepant for several of the important fission products listed in Table 1 and the higher actinides given in Table 2. Radiative capture measurements on such targets as ^{79}Se, ^{93}Zr, ^{126}Sn, and ^{135}Cs in the epithermal neutron energy region would be very useful. Similarly, fission and/or capture measurements in the thermal/epithermal region on several of the higher actinides are needed, particularly ^{232}Pa, ^{238}Np, and ^{242}Am. A new experiment by Moore et al. is in progress at the Los Alamos WNR/LANSCE facility to measure the fission cross sections of ^{238}Np, ^{242}Am, and ^{232}Pa, using radioactive targets made at the Los Alamos Ion Beam Facility. Early results for the 2.1-day ^{238}Np(n,f) and 1.3-day ^{232}Pa(n,f) cross sections from 0.01 eV to 50 keV were reported at the Gatlinburg conference.[17]

- Nuclear Models in LAHET Code. Extensive comparisons have been made of LAHET calculations of (p,xn) neutron emission spectra at different emission angles to measurements, for example, with 113- and 256-MeV protons on thin and stopping-length targets.[11,12] Such measurements have been very useful in developing and validating LAHET, and additional ones at other energies would be useful. Most importantly, measurements of proton or neutron-induced spallation nuclide yields, such as those in progress by Ullmann et al.[5] described in Sect. V, are required to test and improve the models in codes such as LAHET. Additionally, an integral experiment[18] has been performed at WNR/LANSCE that provides direct measurements of neutron yields (using a manganese bath setup) and energy-angle distributions of neutrons from targets that simulate the ATW, APT, and ABC (plutonium burner) concepts. In this experiment the targets were bombarded with 400-MeV and 800-MeV protons. The energy-angle distribution measurements are still being analyzed, but the absolute neutron per proton yield data has been reduced and is found to agree exceedingly well with LAHET calculations.[18]

VII. Conclusions

In addition to the summary of nuclear data needs in the previous sections, a number of more general conclusions and recommendations are possible from this brief assessment of nuclear data needs for ADTT systems.

- Nuclear models in LAHET should be improved as needed when neutron emission and spallation mass distribution measurements are available.

- Effects of direct formation of isomeric states in spallation process should be assessed.

- Results from new cross section experiments (^{232}Pa, ^{238}Np, etc.) should be incorporated into evaluated data libraries as they become available.

- The impact of nuclear data on safety questions should be carefully assessed. For example, the uncertainty in delayed neutron fractions for higher actinides could be important.

- Full neutron data evaluations adequate for transport calculations should be provided for all materials that are present in significant quantity.

- Improvements should be made in the massive activation cross section and decay libraries used in transmutation calculations, especially for reactions leading to isomeric states, for (n,γ) reactions in general, and for isomer target nuclei. Systematic use of modern theory codes is recommended.

- Extension of neutron data files to higher energies is desirable, so that the transition from LAHET to HMCNP calculations would occur in the 100 - 200 MeV range rather than the present energy boundry of 20 MeV. The physics used to determine cross sections would be much better, especially for lighter elements, and transport calculations with state-of-the-art transport codes like HMCNP would be possible to much higher energies.

VIII. Acknowledgments

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References

1. A. J. Koning, "Review of High Energy Data and Model Codes for Accelerator-Based Transmutation," Netherlands Energy Research Foundation report ECN-C--93-005 (1993).

2. A. J. Koning, "Requirements for an Evaluated Nuclear Data File for Accelerator-Based Transmutation," Netherlands Energy Research Foundation report ECN-C--93-041 (1993).

3. J. Kopecky, H. A. J. van der Kamp, H. Gruppelaar, and D. Nierop, "The European Activation File EAF-3 with Neutron Activation and Transmutation Cross Sections," Netherlands Energy Research Foundation report ECN-C--92-058 (1992).

4. S. F. Mughabghab, M. Divadeenam, and N. E. Holden, *Neutron Cross Sections*, V. 1, Part A, Z = 1-60 (Academic Press Inc., 1981); S. F. Mughabghab, *Neutron Cross Sections*, V. 1, Part B, Z = 61-100 (Academic Press Inc., 1984).

5. R. E. Prael and H. Lichtenstein, "User Guide to LCS: The LAHET Code System," Los Alamos National Laboratory informal report LA-UR-89-3014 (1989).

6. J. F. Briesmeister, "MCNP - A General Monte Carlo N-Particle Transport Code," Los Alamos National Laboratory report LA-12625-M (1993).

7. W. B. Wilson, T. R. England, E. D. Arthur, C. A. Beard, C. D. Bowman, L. N. Engel, A. Gavron, D. C. George, L. L. Daemen, H. G. Hughes, III, W. W. Kinnison, R. J. LaBauve, D. M. Lee, H. Lichtenstein, P. W. Lisowski, D. W. Muir, A. P. Palounek, R. T. Perry, E. J. Pitcher, R. E. Prael, G. J. Russell, G. Sanders, L. S. Waters, P. G. Young and H-J Ziock, "Accelerator Transmutation Studies at Los Alamos with LAHET, MCNP, and CINDER'90," Proc. Workshop on *Simulating Accelerator Radiation Environments*, Jan. 11, 1993, Santa Fe, New Mexico (LA-UR-93-3080].

8. R. Prael, "A Review of Physics Models in the LAHET Code," NEANSC Specialist Meeting on *Intermediate Energy Nuclear Data*, May 10 - June 1, 1994, Issy-les-Moulineaux, France.

9. R. E. Prael, "LAHET Benchmark Calculations of Differential Neutron Production Cross Sections for 113 MeV and 256 MeV Protons," Los Alamos National Laboratory informal report LA-UR-89-3347 (1989).

10. R. E. Prael, "LAHET Benchmark Calculations of Neutron Yields from Stopping-Length Targets for 113 MeV and 256 MeV Protons," Los Alamos National Laboratory informal report LA-UR-90-1620 (1990).

11. M. M. Meier et al., "Differential Neutron Production Cross Sections and Neutron Yields from Stopping-Length Targets for 113-MeV Protons," Los Alamos National Laboratory report LA-11518-MS (1989).

12. M. M. Meier et al., "Differential Neutron Production Cross Sections and Neutron Yields from Stopping-Length Targets for 256-MeV Protons," Los Alamos National Laboratory report LA-11656-MS (1989).

13. J. L. Ullmann, P. Staples, G. Butler, M. Fowler, A. Gavron, R. Gritzo, D. Jagnow, J. D. King, R. Laird, P. W. Lisowski, D. Mayo, R. O. Nelson, L. Waters, S. A. Wender, J. Wilhelmy, W. Wilson, M. A. Yates, and C. Zoeller, "Thick Target Spallation Product Yields from 800 MeV Protons on Tungsten," Proc. Int. Conf. on *Nuclear Data for Science and Technology*, May 9-13, 1994, Gatlinburg, Tennessee, to be published.

14. P. G. Young, E. D. Arthur, and M. B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," Proc. ICTP Workshop on *Comp. and Anal. of Nucl. Data Relevant to Nucl. En. and Safety*, 10 Feb. - 13 Mar., 1992, Trieste, Italy; *ibid*, Los Alamos National Laboratory report LA-12343-MS (1992).

15. M.B. Chadwick and P.G. Young, "Application of Multistep Compound and Multistep Direct Models for Data Evaluation," Proc. Sym. on *Nuclear Data Evaluation Methodology*, Upton, NY, 12-16 October 1992, (Ed. C. L. Dunford, World Scientific Press, Singapore, 1993) p. 424.

16. D. W. Muir and W. B. Wilson, "Validation of a Large Activation Cross-Section Library," Proc. Int. Conf. on *Nuclear Data for Science and Technology*, May 9-13, 1994, Gatlinburg, Tennessee, to be published.

17. M. S. Moore, P. E. Koehler, P. E. Littleton, G. G. Miller, M. A. Ott, L. J. Rowton, W. A. Taylor, J. B. Wilhelmy, M. A. Yates, A. D. Carlson, Y. Danon, R. Harper, R. Hilki, and N. W. Hill, "Development of a Technique for Measuring Cross Sections of Interest to Accelerator Transmutation of Waste (ATW)," Proc. Int. Conf. on *Nuclear Data for Science and Technology*, May 9-13, 1994, Gatlinburg, Tennessee, to be published.

18. G. L. Morgan, M. A. Yates, T. Stratton, M. S. Moore, J. L. Ullmann, M. DeVolder, R. E. Prael, Green, F. Venneri, Heath, L. Waters, and Thornton, personal communication (May, 1994).