Review of Nuclear Data Needs for Fusion Energy Development

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Nuclear data is essential for the development of environmentally attractive fusion power plants. A long-term approach has been taken for the development of fusion nuclear data. Remarkable progress has been made that established an internationally available nuclear data library. Review of nuclear data needs is continuing and deficiencies are identified based on recent trends in fusion energy development. Benchmark testing and experimental verification activities have been continuing to improve the evaluated nuclear data library.

Introduction

A common goal of fusion energy development is to secure an inexhaustible energy source that is economically competitive and environmentally attractive. Low cost electricity generation with fusion can only be achieved by adopting the development path that eventually leads to a smaller fusion core and higher thermal power density. The resulting high neutron wall loading and surface heat flux will require the development of exotic blankets and plasma facing components such as the liquid wall using lithium, lithium-lead, lithium-tin, and flibe.[1-2] Reduction of long-lived radwaste volume is a very important objective of the development of environmentally attractive fusion power plants. Recycle and reuse of fusion reactor materials can be a very attractive strategy that can allow fusion energy to achieve the environmental objective.[3]

Nuclear data, however, is essential for providing the necessary parameters of the anticipated fusion power plants. Tritium breeding, which is necessary in a deuterium-tritium (D-T) fueled fusion plasma, can be predicted only when reliable nuclear data is available. Nuclear heating rate, which includes total thermal power output and localized power density, is essential for the assessment of high power density blankets. Activation of reactor materials is fundamental for the assessment of radioactive safety and long-term waste issues. Both nuclear heating and activation can only be predicted when the available nuclear data is complete and reliable.

Fusion Nuclear Data Development

Nuclear data needed include at least the following for the candidate fusion reactor materials:[4]

- Double-differential cross sections,
- Gamma production cross sections,
- Neutron multiplication reactions namely Li-7(n,n'α), Be(n,2n), and Pb(n,2n), and
- Activation cross sections.

The fusion nuclear data base has been evolved by first adopting the large volume of data base already or being developed for the fission reactor technology and then improving it through measurements and evaluations of data at 14 MeV. International interest in fusion energy development has promoted the cooperation in fusion nuclear data development. The measurement of basic nuclear data has been progressed worldwide through the review of nuclear data status and compilation of nuclear data requests lists maintained by the IAEA and the OECD/NEA. The nuclear data measurement and evaluation activities have also been encouraged by the internationally cooperative interests in nuclear physics, as well as in the development of fusion nuclear technologies for energy applications. These efforts have led to the compilation, under the coordination of the IAEA Nuclear Data Section, a complete set of fusion evaluated nuclear data libraries, FENDL, for fusion power plant development.[5] In addition to the evaluated libraries, FENDL also consists of processed working libraries for neutron transport and activation calculations.

The evaluated libraries include the general-purpose library (FENDL/E), activation library (FENDL/A), dosimetry library (FENDL/DS), decay data library (FENDL/D), and incident charged-particle reaction data library (FENDL/C). The processed working libraries are the continuous energy cross section library for Monte-Carlo transport calculations (FENDL/MC), the multi-group cross section library for discrete-ordinates transport calculations (FENDL/MG), and the uncertainty library (FENDL/U).

The first version of the incident charged-particle reaction data library (FENDL/C-1.0) consists of major fusion reactions from ENDF/B-VI, namely H-2(d,n)He-3, H-2(d,p)H-3, H-3(d,n)He-4, He-3(d,p)He-4, and H-3(t,2n)He-4. A processed working data library, containing Maxwellian-averaged reaction rates, is also available from the Livermore Thermonuclear Data File (TDF). The general-purpose library, FENDL/E-1, consists of neutron and photon interaction cross sections. The neutron interaction cross sections are selected from:

ENDF/B-VI -- H-1, H-3, Li-6, Li-7, Be-9, B-10, B-11, C-12, O-16, F-19, P, S, Cl, K, V-51, Cr-50, Cr-52, Cr-53, Cr-54, Mn-55, Fe-54, Fe-56, Fe-57, Fe-58, Co-59, Ni-58, Ni-60, Ni-61, Ni-62, Ni-64, Cu-63, Cu-65, Ba-134, Ba-135, Ba-136, Ba-137, Ba-138, W-182, W-183, W-184, W-186, Pb-206, Pb-207, and Pb-208;

JENLD-3.1 -- Na-23, Mg, Al-27, Ca, Ti, Mn-55, Mo, Ta-181, and Bi-209;

BROND-2) -- H-2, N-14, N-15, Si, Zr-90, Zr-91, Zr-92, Zr-94, Zr-96, Nb-93, and Sn.

The photon interaction cross sections are from:

ENDF/B-VI -- H, Li, Be, B, C, N, O, F, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zr, Nb, Mo, Sn, Ba, Ta, W, Pb, and Bi.

Several new or improved evaluations have been proposed for the updated version, FENDL/E-2.0. The criteria established for the selection of these evaluations are that the candidate evaluations have to include the following information:

Gamma ray production cross section,
Neutron and charged-particle emission data in File 6 format,
File 1 descriptive information,
Recoil distributions in File 6 format for major structural materials, and
Energy balance must be better than 2% for all energies.

The selected FENDL/E-2.0 evaluations that meet the above criteria include:[5]

ENDF/B-VI -- Si-28, Si-29, and Si-30;
JENDL-FF -- Be-9, C-12, N-14, O-16, V-51, Zr, Nb-93, Mo, and W;
BROND-2 -- H-2 and Sn; and
EFF-3 -- Al-27 and Fe-56.

The decay data library, FENDL/D-1.0, consists of approximately 2900 nuclides, which are extracted from ENDF/B-VI and ENSDF, and contains the basic information needed for activation analysis, namely isotope, half-life, decay mode, daughter nuclide and branching ratio, and decay gamma intensity and energy spectrum. The activation data library, FENDL/A-2.0, is a version evolved from merging important reactions and the basic library recommended by an IAEA/NDS expert panel. The important reactions include 404 reactions selected from JENDL-3.2/A, EAF-4.1, ADL-3, IAEA/CRP for long-lived activation cross sections [6], and the first version FENDL/A-1.0. It is noted that the IAEA/CRP activity (1988-96) has measured and evaluated a number of important reactions leading to the generation of long-lived radionuclides. These include Al-27(n,2n)Al-26, Ni-62(n,γ)Ni-63, Cu-63(n,p)Ni-63, Mo-94(n,p)Nb-94, Mo-98(n,γ)Mo-99(Tc-99), Ag-109(n,2n)Ag108m, Eu-151(n,2n)Eu-150, Eu-153(n,2n)Eu152, Dy-158(n,p)Tb-158, Tb-159(n,2n)Tb-158, Ho-165(n,γ)Ho-166m, Hf-179(n,2n)Hf-178n, W-182(n,n'α)Hf-178n, Re-187(n,2n)Re-186m, Ir-191(n,γ)Ir-192n, and Ir-193(n,2n)Ir-192n. The basic library includes 12,972 reactions mainly from EAF-4.1. Due to the concern for consistent identification of daughter nuclides, the EAF-4.1 decay data library is also used as FENDL/D-2.0.

Status of Fusion Nuclear Data

Due to the recent emphasis of fusion science research, especially in the U.S., the urgency of nuclear data needs for power reactor development is also subjected to adjustment. Accordingly, the priority in the nuclear data requests list submitted to the OECD/NEANSC has been degraded from the high priority to a lower second or third priority. However, new requests have been added. These are primarily for the differential data and activation reaction data for Sn isotopes. Review and evaluation of nuclear data for Sn isotopes for neutron transport and activation calculations are needed for the assessment of using Sn-Li bimetallic material in the fusion power plants. Table 1 lists these recent requests.

Assessment of low activation materials can be reliable only when the nuclear data library used in the calculation is complete and accurate. One of the important issues of using SiC-SiC composites as low activation structural material in a fusion blanket is the production of long-lived radionuclide, Al-26 (half-life 740,000 y), from Si via the two step reactions: Si-28(n,n'p)Al-27 and Al-27(n,2n)Al-26. Using the recently updated evaluations for Si-28(n,n'p)Al-27 cross section, it shows a significantly low production rate of Al-27. Experimental verification of the evaluated reaction cross section is still needed.

Recycle and/or reuse of fusion reactor materials is a very unique strategy to reduce the long-term radioactive waste to be generated in the future D-T fueled fusion power plants. The concentration (and thus the activity) of long-lived radionuclides after many cycles of reusing the reactor materials depends not only the production cross sections, but also the removal cross sections. There is a need to review the removal cross sections for the important fusion specific long-lived radionuclides such as Nb-94, Tc-99, Ag-108m, Al-26, and so on.

Benchmark data testing and experimental data verification are essential for the validation of the evaluated nuclear data. They are required to assess the quality of the evaluated nuclear data library, a necessary procedure to maintain the high quality of the FENDL and other libraries for fusion applications. Under the coordination of the IAEA/NDS, benchmark experiments, which include integral neutronics and activation experiments, have been compiled and used for data validation purposes.[6-8] Table 2 shows the list of these benchmark experiments. Data testing using these benchmark experiments has been applied for the selection of the FENDL/E-2.0 and FENDL/A-2.0 libraries. A new initiative to establish benchmark problems for Sn, however, appears to be needed since no such experiment exists, as shown in Table 2.

Conclusions

Nuclear data is essential for the development of environmentally attractive fusion power plants. A long-term approach has been taken for the development of fusion nuclear data and has achieved significant progress. An international nuclear data library, FENDL, has been established and used in various national and international fusion research projects. Review of nuclear data needs is constantly performed based on the current trends in fusion energy development and deficiencies are identified accordingly. Benchmark data testing and data verification experiments have been important processes to improve the completeness and to control the quality of available nuclear data for fusion energy development.

Table 1. Nuclear Data Requests for Fusion Submitted to OECD/NEANSC

Type of Reactions/Nuclides/Comments
I. Double-differential cross sections at energies - 6, 8, 10, 12, and 14 MeV; accuracy - 10%. O, Si, V, Fe, W, Pb, Li-6, Li-7, Be, B-10, B-11, C, Cr, Mn, Ni, Sn
II. Neutron multiplication reactions: 3% from threshold to 15 MeV. Li-7(n,n'p), Pb(n,2n), Be(n,2n)
III. Activation cross sections: 20% accuracy unless otherwise specified; threshold reaction - threshold to 15 MeV; n,γ reactions: - thermal to 1 MeV; dosimetry cross section – 5 to 15 MeV (5%). Waste disposal concern: N-14(n,p)C-14; Ti-48(n,α)Ca-45(n,α)Ar-42; Fe-58(n,γ)Fe-59; Ni-63(n,α)Fe-60; Ni-64(n,2n)Ni-63; Cu-65(n,t)Ni-63; Mo-94(n,p)Nb-94; W-182(n,n'α)Hf178m2; W-186(n,n'α)Hf-182; Ca-45(n,α)Ar-42; Sn-120(n,γ)Sn-121m; Sn-125(n,γ)Sn-126; Sn122(n,2n)Sn121m; Sn112(n,n'α)Cd108 Materials recycling concern: V-50(n,2n)V-49 Dosimetry cross section: Zn-64(n,p)Cu-64 Decay heat and radiological hazard concerns: Pb-204(n,p)Tl-204; Pb-204(n,t)Tl-202; Sn122(n,γ)Sn123; Sb121(n,γ)Sb122; Sn120(n,p)In120m; Sn119(n,p)In119; Sn118(n,p)In118m; Sn117(n,p)In117m; Sn116(n,p)In116m; Sn115(n,p)In115m; Sn114(n,2n)Sn113; Sn112(n,2n)Sn111; Sn112(n,γ)Sn113, Al-27(n,n'α)Na-23; Si-29(n,t)Al-27 Inconsistency in experiment and evaluation: V-51(n,n'α)Sc-47 Neutron absorption in Sn: Sn(n,γ) from thermal to 15 MeV; Natural element and isotopic n,γ cross sections.
IV. Near-term (e.g., ITER) and very low activation power reactors Nuclear heating in the super-conducting TF magnet 1. Cu(n,xn): Double-differtial cross sections at 6, 8, 10, 10, 12, and 14 MeV; 10% accuracy. 2. Cu-63(n,γ)and Cu-65(n,γ): 10% accuracy at energies from thermal - 1 MeV. 3. Ta-181(n,γ)Ta-182: 10% accuracy from thermal - 1 keV; resonance region is important to determine the self-shielding effect. Decay heat in 316SS and Inconel alloy 4. Mn-55(n,γ)Mn-56: 10% accuracy at energies from thermal - 1 MeV. 5. Ta-181(n,γ)Ta-182: 10% accuracy at energies from thermal to 1 keV. See IV-3. Waste management for reactor components (316SS and Inconel structures) 6. Ni(n,x)Co-60: Threshold - 15 MeV; 20% accuracy; principal reactions needed: Ni-60(n,p) and Ni-61(n,n'p). Waste disposal issue for SiC 7. Si(n,x)Al-27: Threshold - 15 MeV; 20% accuracy; primarily Si-28(n,n'p); recommended measurements: Si-28(n,xp) at 14 MeV.
V. Alpha slowing-down dosimetry reactions (20% accuracy) 1. O16(n,2n)O15: from threshold to 20 MeV. 2. O16(γ,n)O15: from 17 MeV to 20 MeV. 3. Be9(n,d)Li8: from threshold to 20 MeV. 4. Be9(n,p)Li9: from threshold to 16 MeV. 5. Ne20(n,2n)Ne19: from threshold to 20 MeV. 6. Ne20(γ,n)Ne19: above 17 MeV. 7. Ne22(n,α)O19: from threshold to 16 MeV. 8. Ne20(n,t)F18: from threshold to 20 MeV. 9. Mg24(n,t)Na22: from threshold to 20 MeV. 10. Si30(n,He-3)Mg28: from threshold to 20 MeV. 11. Si28(n,t)Al26: from threshold to 20 MeV. 12. T-He4 scattering cross sections: He-4 energy is from 1 to 3.5 MeV; high priority is given at 3.5 MeV; more precise energy transfer data is needed.

References used for Table 1:

1. The most recent U.S. data requests list compiled by ORNL.
2. ECN report, EAF-Doc-004, March 1994
3. Personal communication with R. Fisher, General Atomics, regarding nuclear data needs for Tokamak diagnostics, June 1994.
4. Personal communication with Don Smith, ANL, and Yujiro Ikeda, JAERI, March 1996.

Table 2. Experimental Benchmarks for FENDL Data Testing

Material	Geometry	Measured Quantity	Facility
• Integral Neutronics Experiments			
Li2O, Be, C, Liquid O, Liquid N, Fe, Pb	Cylinder Slab	Angular neutron spectra, 30 keV - 15 MeV	JAERI (FNS)
Li2O, Be, C, Fe, Cu, W, V	Cylinder Slab	Neutron and gamma spectra, reaction rate, heating rate	JAERI (FNS)
SS316L	Slab	Neutron spectra, Reaction Rates, gamma heating	JAERI, ENEA, CEA
Be, Be-Li, Fe, Ni	Sphere	Neutron leakage spectra	Osaka U. (OKTAVIAN)
Li, Pb-Li, Pb-Li-C, Be-Li, Be-Li-C	Sphere	Tritium production rate	Osaka U. (OKTAVIAN)
Be, Al, Fe, Ni, Pb, V	Sphere	Neutron leakage spectra	IPPE
Be (Sphere), Fe	Slab	Reaction rates	KIAE
Be	Sphere	Neutron Reaction Rates	INEL
Fe (Slab), Pb, V	Sphere	Neutron and gamma spectra	TUD
Be, Fe, Pb, V	Sphere	Neutron Reaction Rates	SWINPC
Be	Sphere	Total neutron leakage	FZK
• Induced Radioactivity Measurements			
Al, Co, Cr, Cu, Fe, Mo, Mn, Nb, Ni, Si, Ta, Ti, V, W, Zr	Small Samples	Induced radioactivity and Heating Rates	JAERI, ENEA, FZK, TUD, KIAE

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[8] Fischer, U., et al.: “Neutronics and Nuclear Data: Achievements in Computational Simulations and Experiments in Support of Fusion Reactor Design,” Proc. International Symposium on Fusion Technology, September 1999, Rome, Italy (to be published).