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REVIEW OF THE NUCLEAR DATA STATUS AND REQUIREMENTS FOR FUSION REACTORS

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Abstract: Requirements and status of nuclear data for fusion reactors are reviewed and discussed. Special emphasis is on the review of neutron multiplication cross-sections, tritium production in ^{7}Li, and activation cross-sections leading to the production of long-lived radionuclides.

[nuclear data for fusion reactors, ^{7}Li $(n,2n)$T, ^{9}Be $(n,2n)$, Pb $(n,2n)$, long-lived activation cross-sections]

Introduction

The development of D–T fueled fusion power reactors is now poised on the verge of plasma break-even and plans are being made to move ahead into the ignition stage. The designs of experimental reactors to conduct plasma ignition experiments such as the Compact Ignition Tokamak (CIT)[1], and to test the engineering components for power reactors such as the Engineering Test Reactor (ETR)[2], Next European Torus (NET)[3], and Fusion Engineering Reactor (FER)[4] are underway. The reactor materials required to fabricate the first wall, blanket, shield, and magnet components of a fusion power reactor have been identified in various reactor studies. Neutron differential data for these materials are essential for determining the neutron spectra in each component. Neutron reaction data as well as gamma-ray production and transport data are necessary to determine various nuclear performance characteristics including nuclear heating in these reactor components. The status of the nuclear data for relevant fusion reactor materials was summaried recently[5-6]. Discrepancies and requirements for improvements in these data were identified. In this paper we present an updated review summarizing all these fusion nuclear data efforts. Special emphasis will be on the review of neutron multiplying cross-sections, tritium production in ^{7}Li, and activation cross-sections leading to the production of long-lived radionuclides.

Nuclear Data Requirements for Fusion Reactors

An excellent review of the nuclear data requirements for D–T fusion reactors was given at the recent IAEA Advisory Group Meeting in Gaussig, German Democratic Republic[7]. The nuclear data required according to the functional needs of a D–T fusion reactor are summarized as follows: (1) neutron flux determination: total cross-sections, neutron emission cross-sections (including double differential data), neutron multiplication cross-sections, and dosimetry cross-sections; (2) fuel production: mainly ^{6}Li (n,α)T and ^{7}Li $(n,n'\alpha)$T cross-sections for pure fusion concepts, and ^{232}Th (n,γ) and ^{238}U (n,γ) for fission-fusion hybrid concepts; (3) neutron multiplication: mainly ^{9}Be $(n,2n)$ and Pb $(n,2n)$ cross-sections for pure fusion concepts, and ^{232}Th $(n,2n)$, ^{238}U (n,γ) and fast fission cross-sections for thorium and uranium for hybrid concepts; (4) safety and radiation hazard: activation cross-sections and decay data; (5) radiation damage: charged-particle (hydrogen and helium) production cross-sections and transmutation cross-sections; (6) power generation: charged particle production cross-sections and gamma-ray production cross-sections; and (7) fusion reactions: D-D and D–T charged-particle nuclear and physics data.

Fusion materials are those employed in fusion reactor components including first wall/divertor/limiter, blanket, magnet shield, magnet, and biological shield system. These fusion reactor systems have been the subject of fusion reactor design studies for many countries participating in fusion energy research. Given below is a list of more promising blanket systems under development among various countries:

Pure Fusion

- Systems with no neutron multiplier
  - — Lithium self-cooled/vanadium alloy structure
  - — Li_2O solid breeder/helium coolant/ferritic steel structure
  - — $Li_{17}Pb_{83}$ self-cooled/vanadium alloy structure
  - — Lithium breeder/helium coolant /ferritic steel structure
  - — $LiF{\cdot}BeF_2$ (FLiBe) self-cooled/vanadium alloy structure
- Systems with neutron multiplier (beryllium or lead)
  - — Water-cooled blanket concepts
    Solid breeders — Li_2O, Li_4SiO_4, $LiAlO_2$, etc.
    Liquid breeder — $Li_{17}Pb_{83}$
    Lithium salt in aqueous solution — $LiNO_3$, LiOH, etc.
  - — Helium-cooled blanket concepts
    Li_4SiO_4 and $Li_{17}Pb_{83}$ breeders
- Low activation blanket systems
  - — Li_2O or Li_4SiO_4 breeder with beryllium/helium coolant/ceramic or graphite composite structure

Fusion-Fission Hybrid

- Fast fission — thorium and uranium neutron multiplier
- Fission suppressed — beryllium and lead neutron multiplier

Magnet shield designs are composed of a combination of the following materials: W, B_4C, Pb, moderating materials, and structural alloys. The coolant for the shield is either water or helium, although in some self-cooled designs, it may be the breeder/coolant itself.

The materials needed for the development of the above blanket and shield systems are summarized in Table 1. Note

TABLE 1

Potential Fusion Materials
(Ref: 1986 IAEA Advisory Group Meeting
on Nuclear Data for Fusion Reactor Technology)

Component (Zone)	Major Element
Structure	Fe, Cr, Ni, Mn, V, Ti, Al, Si, C
Breeder/Coolant	Li, H, O, Pb, F, He, Be, Al
Neutron Multiplier	Be, Pb
Magnet Shield	C, B, W, Pb, H, O + structure
Magnet	Cu, Sn, Nb, Al, N, He + structure
First Wall/Divertor/Limiter	C, Cu, W, Be + structure
Biological Shield	Ca, Si, Ba, O + structure
Hybrid Blanket	Th, U, Pu

*Low Activation (Low Level Waste Disposal) design is receiving more attention in recent development of pure fusion reactors. Niobium and molybdenum structures are being avoided.

that low activation (low level waste disposal) design is receiving more attention in recent development of electricity producing fusion reactors. As a result of this tendency, niobium and molybdenum are being avoided as structural materials, as shown in Table 1[8].

Status of the Nuclear Data

The status of the nuclear data for fusion reactors was reviewed at the 1986 IAEA Advisory Group Meeting[7]. Tables 2 and 3 summarize the results of the review for transport and other reaction cross-sections. We have done additional review to comment on the progress of nuclear data development since the 1986 IAEA AGM meeting. These are nuclear data related to tritium production, neutron multiplication, and low activation materials. In the following we discuss in detail each of these areas.

^{7}Li $(n,n'\alpha)$T Cross-Section

This reaction cross-section is essential for lithium self-cooled and helium-cooled lithium-oxide solid breeder blanket concepts as far as tritium breeding is concerned. Since 1981 there have been more than a dozen measurements performed for ^{7}Li $(n,n'\alpha)$ cross-sections, and most of them were in 13 to 15 MeV energy range[9]. As a result of these measurement activities, the 16th International Nuclear Data Committee Meeting in Beijing, China (October 1987) removed ^{7}Li $(n,n'\alpha)$ cross-section from the discrepancy list. New evaluations based on the experimental values are being performed for the JENDL-3, EFF-2, and ENDF/B-VI files. Table 4 shows the results of a new evaluation for ENDF/B-VI by Young and Rutherford[9]. These evaluated cross-sections are also compared with a previous version of ENDF/B, EDNF/B-V.2. What we may conclude from Table 4 are (1) the new evaluation may

TABLE 2

Accuracy Needed and Status for Transport Cross-Sections
(Ref: 1986 IAEA Advisory Group Meeting on Nuclear Data
for Fusion Reactor Technology)

Nuclear Data	Component Breeder/Multiplier %	 Met	 Shield %	 Met	 Magnet %	 Met	 Hybrid %	 Met
Total Cross-Section								
$E < 10$ MeV	3	P	3	Y	3	Y	1	P
$E > 10$ MeV	1	N	1	N	3	Y	1	P
Neutron Emission	10	N	3	N	20	P	10	P
Neutron Multiplication	3	N	–	–	–	–	5	Y
Elastic Angular Distribution	10	N	3	N	20	P	10	Y

Y — Experimental Data exist and evaluation may incorporate such data
P — Partially Met
N — Experimental Data DO NOT exist or DO NOT satisfy requested accuracy

TABLE 3

Accuracy Needed and Status for Other Reactions[7]

Function	Accuracy (%)	Met	Comments
Tritium Production			
^{6}Li (n,α)	5	Yes	Standard evaluation
^{7}Li $(n,n'\alpha)$	3	Yes (Evaluation)[†]	New evaluations completed to 2% at 14 MeV by Young and Rutherford[9]
Neutron Multiplication			
^{9}Be $(n,2n)$	3	No	Discrepancies in total neutron multiplication
Pb $(n,2n)$	3	No	Discrepancies in total neutron multiplication
Radiation Damage			
Recoil Spectra, Gas Production, and Transmutation	20	Yes	
Radiation Hazards			
Activation Cross-Sections	20	Partially	Status being reviewed; needs long-lived activation data
Decay Data	5	Partially	Status being reviewed; needs improvement on long-lived radionuclides
Fusion Reactions			
D (T,α) n	5	Yes	Better than 3% data available
Scattering Cross-Sections	20	Yes	Better than 10% data available

[†] Update since the 1986 IAEA Advisory Group Meeting.

TABLE 4

New Evaluation on ^{7}Li $(n, n'\alpha)$ Cross-Sections and Detailed Comparison with ENDF/B-V.2 near 14 MeV

	ENDF/B-V.2*		Young & Rutherford**		
E_n (MeV)	σ (b)	$d\sigma$ (%)	σ (b)	$d\sigma$ (%)	% Chg.
13.0	0.3210	5.4	0.3188	2.4	−06
13.5	0.3125		0.3110		−0.5
14.0	0.3042	3.1	0.3026	1.8	−0.5
14.5	0.2960		0.2939		−0.7
15.0	0.2879	4.8	0.2850	1.8	−1.0
15.5	0.2798		0.2748		−1.8
16.0	0.2717	35.0	0.2646	4.8	−2.7

*(1981); **(1987)

achieve less than 3% statistical error at neutron energies from 13 to 15 MeV; and (2) the difference in this energy range between ENDF/B-V.2 and the present evaluation is less than 1%.

Neutron Multiplication Cross-Sections

Neutron multiplication from 14 MeV D–T neutrons is a very important nuclear reaction process for fusion reactors. It is required for most fusion blankets other than liquid lithium self-cooled or helium-cooled Li_2O concepts. Beryllium and lead are the only practical neutron multiplication materials which are not fissionable. Beryllium is particularly important because of its superior neutron multiplication capability and other advantageous material properties such as low activation, high melting point, and good chemical compatibility with other structural alloys. Beryllium has been recently selected as the primary neutron multiplication material for the driver blanket of the International Thermonuclear Engineering Reactor (ITER) study, a cooperative project of the U.S., Soviet Union, European Communities, and Japan.

However, the beryllium and lead neutron multiplication data are not without problems. The measured $(n, 2n)$ cross-sections for these two materials at 14 MeV are sparse. The evaluated cross-sections showed discrepant values with the measured ones. The integral neutron leakage multiplication experiments performed up to now are not satisfactory for the evaluation of calculated results. We believe that more data development efforts are needed in two areas for beryllium and lead: (1) basic $(n, 2n)$ cross-sections from 14 to 15 MeV energy and their corresponding neutron emission data; and (2) integral neutron leakage multiplication experiments. The integral experiments are necessary for data testing on the evaluated $(n, 2n)$ and neutron emission cross-sections.

(a) ^{9}Be $(n, 2n)$ Cross-Sections

Table 5 lists the recently evaluated and measured ^{9}Be $(n, 2n)$ cross-sections at 14.1 MeV. As shown in Table 5, the new evaluations in the U.S., ENDL86 (future ENDF/B-VI), and in Japan, JENDL-3T (a temporary version for JENDL-3), are 485 and 542 mb, respectively, for ^{9}Be $(n, 2n)$ cross-sections at 14.1 MeV. The difference between these two evaluations

TABLE 5

Be $(n, 2n)$ Cross-Sections at 14 MeV

Evaluation/Experiment	Cross-Section (b)	Ratio to ENDF/B-VI
ENDF/B-VI (ENDL 86)[10]	0.485	1.00
JENDL-3T[11]	0.542	1.12
ENDF/B-V	0.513	1.06
ENDF/B-IV	0.536	1.11
Kneff *et al.* (1986)[12]	0.506 (8%)	1.04
Measurements to 1978[12]	0.491	1.01
OKTAVIAN Exp. (1987)[11]	0.478 (2.9%)	0.99
OKTAVIAN Exp. (1984)[11]	0.485 (6.2%)	1.00

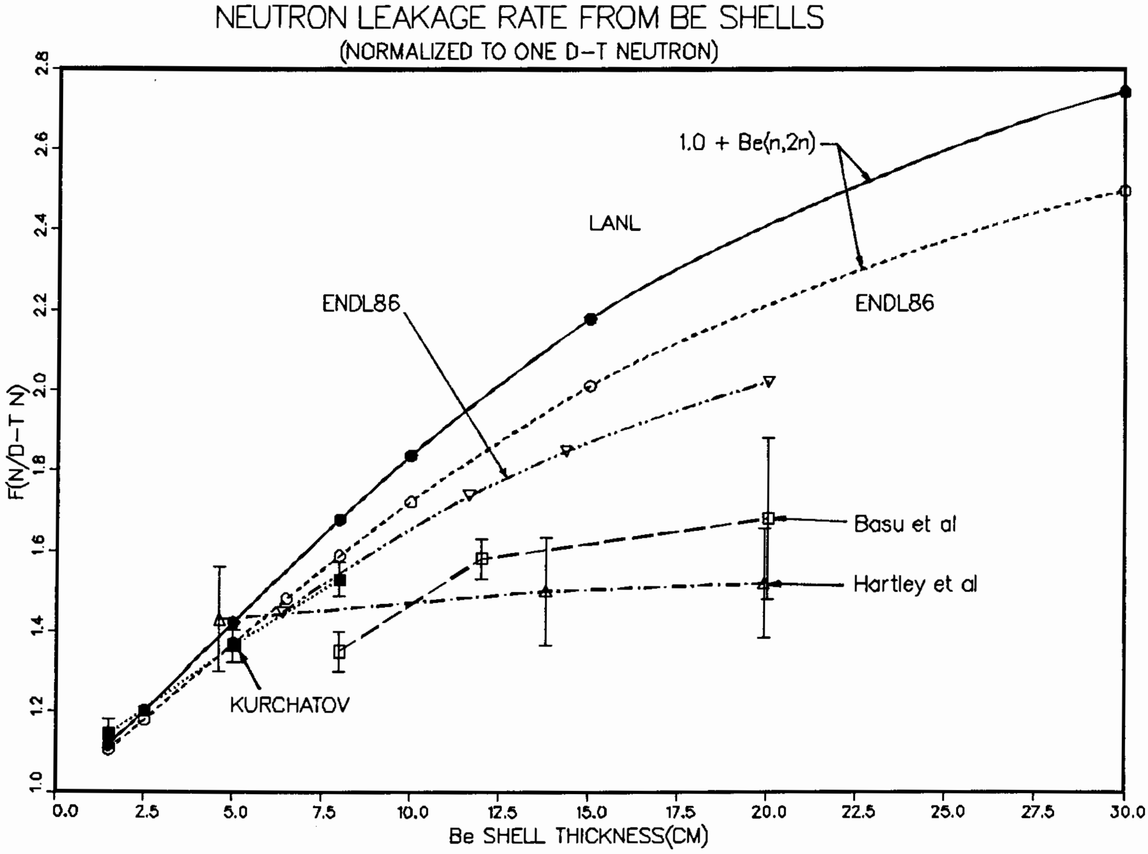

FIG. 1. Measured and calculated neutron leakage multiplication from beryllium assemblies as a function of beryllium thickness.

is more than 10%. The ENDF/B-IV and -V evaluations give values between the two new evaluations and are at least 6% larger than ENDL86. The measured ^{9}Be $(n, 2n)$ cross-sections, however, agree very well with the ENDL86 value, as shown in Table 5, within respective experimental errors. We may conclude, based on these observations, that the ENDL86 evaluation for ^{9}Be $(n, 2n)$ cross-sections at 14.1 MeV gives a reasonable value which is consistent with the experimental results. Note that the measured ^{9}Be $(n, 2n)$ cross-section by the OKTAVIAN group at Osaka University has achieved an accuracy of 2.9%.

Figure 1 summarizes recent integral experiments on beryllium neutron leakage multiplication factors and calculations performed using the ENDL86 evaluation. The experiments are briefly described below: (a) Jülich Experiments — performed in 1979 by Basu *et al.* and reanalyzed by V. Nargundkar *et al.* in 1987[13]. The experimental errors of these measurements range from 3.2% to 12%. Compared to calculations with ENDF/B-IV or ENDF/B-V evaluations, the experimental results are about 20% lower. (b) Kurchatov Experiments — These are total absorption experiments employing a borated water tank[14]. These are all very precise measurements giving an experimental error of about 3%. (c) University of Texas Experiments — Performed recently at the University of Texas at Austin by R. Hartley and N. Hertel[15]. The experimental error reported is 9%. The measured neutron leakage multiplication factors are, in general, lower than those measured by Basu *et al.*

In addition to the above integral experiments, there were also experiments performed at Lawrence Livermore National Laboratory[16]. However, there have been no conclusive results on the total neutron leakage factors yet until the low energy neutron detector calibration is completed[17].

Figure 1 also shows the neutron leakage multiplication factors calculated with the most recent evaluation, ENDL86[18]. The total neutron multiplication factors [1 + Be $(n, 2n)$] calculated with ENDL86 and Los Alamos National Laboratory (Young and Stewart, 1979) evaluations are also shown in Fig. 1 for comparison. Note that the difference between the total and leakage multiplication factors is the fraction of neutrons absorbed in the beryllium sphere due to threshold (n, p), (n, d), (n, t), and (n, α) reactions and capture (n, γ) reactions.

The following comments are given regarding the experiments and calculations shown in Fig. 1: (a) all the integral experiments are not consistent with each other; (b) however, the Kurchatov experiments show consistent results when the zero thickness beryllium point is considered (when the beryllium thickness is zero centimeters, the neutron leakage multiplication should be unity, by definition); (c) the Jülich experiments are not consistent, perhaps owing to the fact that these are not spherical geometry experiments; and (d) the University of Texas experiments are not consistent due to a large experimental error, 9%.

Based on the above comments, we may conclude, as far as beryllium neutron integral experiments are concerned, that (1) we need more beryllium integral experiments at thicknesses, preferably, between 10 and 20 cm; and (2) we need good quality and consistent experiments. The experimental errors should be about 3%, or as accurate as possible.

(b) Pb $(n, 2n)$ Cross-Sections

Table 6 lists the measured and evaluated Pb $(n, 2n)$ cross-sections at 14 MeV. The evaluated values, including those from ENDF/B-V, -IV, and EFF-1, are very consistent, within about 2%, as shown in Table 6. However, the measured values, as also shown in Table 6, are discrepant among themselves by about 20%. Compared with the evaluated values, the measured cross-sections are higher or lower by about 10%, noting that the experimental errors are 7% or less.

Several integral experiments on lead neutron multiplication factors were performed recently: (a) the OKTAVIAN group obtained new results using the lead-lithium sphere leakage spectrum method[11]. Compared to their 1985 measurements, the new results show lower multiplication values and better accuracy (7%); (b) Technical University of Dresden experiment[19] — at a lead thickness of 22.5 cm and an experimen-

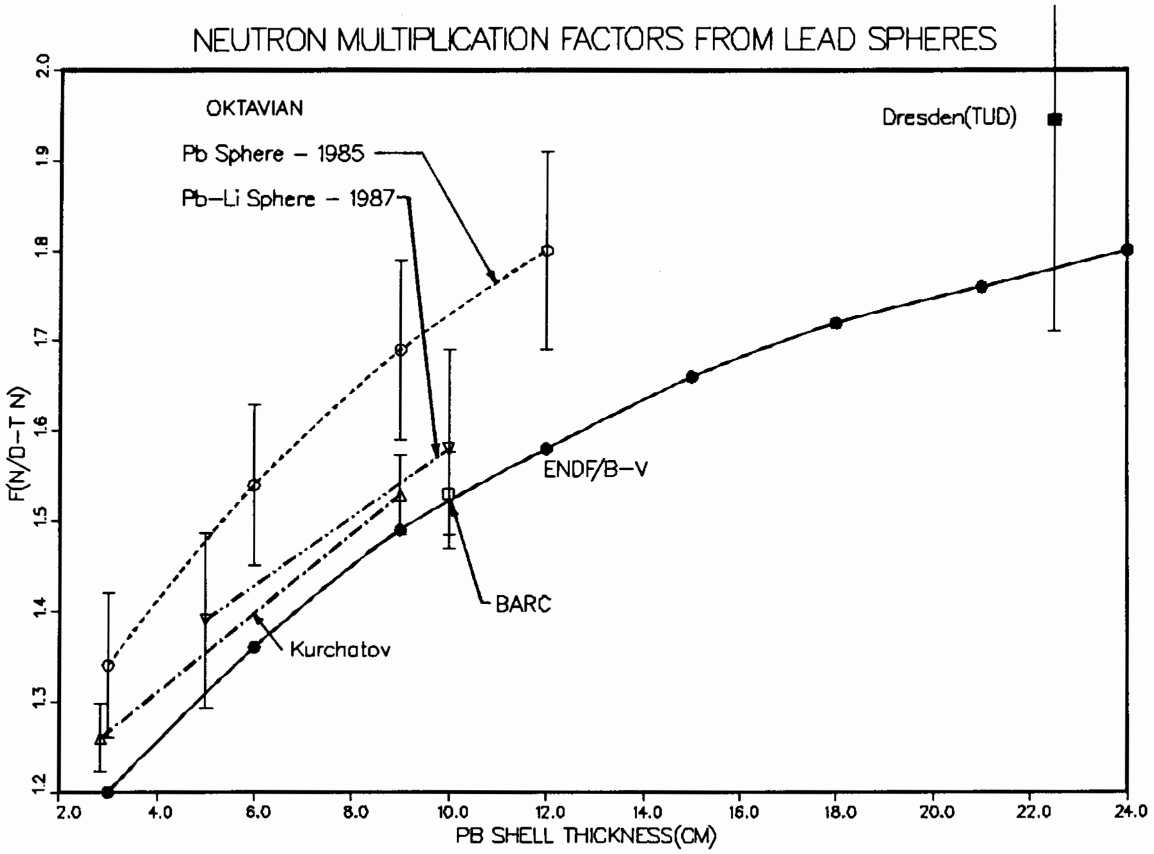

FIG. 2. Measured and calculated neutron multiplication factors in lead assemblies as a function of lead thickness.

TABLE 6

Pb $(n,2n)$ Cross-Sections at 14.1 MeV

Evaluation/Experiment	Cross-Section (b)	Ratio to ENDF/B-VI
ENDF/B-V	2.14	1.00
ENDF/B-IV	2.15	1.00
EFF-1	2.10	0.98
OKTAVIAN (1984)	2.33 (5.2%)	1.09
OKTAVIAN (1987)	2.43 (4.1%)	1.14
Frehaut (1980)	1.95 (7%)	0.91

tal error of 12%; (c) BARC experiment[20] achieved 3% measurements at 10 cm lead thickness; and (d) Kurchatov experiment[14] — also very accurate (2.9%) experiments using the boron tank total absorption technique. Both 5 and 10 cm lead thickness spheres were measured. Figure 2 shows schematically the results of these measurements as a function of lead thickness. The calculations using ENDF/B-V based nuclear data library are also shown in this figure for comparison. Note that in the lead experiment, the parasitic absorption of neutrons in lead is negligibly small because of the harder leakage spectrum due to the poor moderation property of lead.

As clearly shown in Table 6 and Fig. 2, the issue of Pb $(n,2n)$ cross-section and multiplication factor is still in dispute and needs to be resolved by more careful and coordinated research effort.

Activation Cross-Sections

Radioactivity in fusion reactors is primarily induced by D–T neutrons and depends entirely on the materials chosen for constructing the reactor components[21]. Measurement and evaluation activities for 14 MeV neutron activation cross-sections are popular recently[22,23]. The development of a comprehensive activation data library for fusion applications is also in good progress[24-26]. The need for activation cross-sections leading to the production of long-lived (half-life longer than five years) radionuclides has become obvious in the recent years because of the worldwide concerns for the production of high level nuclear waste from fusion reactors[27]. High-priority long-lived activation cross-sections were identified recently[27]. The important energy ranges for these cross-sections are: (a) 14 MeV for most threshold reactions, and (b) 1 keV to 1 MeV for most (n,γ) reactions.

Recent measurements or measurements in progress include the following reaction cross-sections[28-30]: ^{27}Al $(n,2n)$ ^{26}Al, ^{63}Cu (n,p) ^{63}Ni, ^{64}Ni $(n,2n)$ ^{63}Ni, ^{60}Ni $(n,2n)$ ^{59}Ni, ^{94}Mo (n,p) ^{94}Nb, ^{14}N (n,p) ^{14}C, ^{93}Nb (n,p) ^{93}Zr, ^{94}Zr $(n,2n)$ ^{93}Zr, ^{93}Nb $(n,2n)$ ^{92}Nb, and ^{94}Mo $(n,2n)$ ^{93}Mo. Table 7 lists the activation cross-sections which still need to be measured. Note that recently a Coordinated Research Program is being organized by the IAEA to measure some of these cross-sections[31].

Conclusion and Recommendations

Finally, concluding remarks and recommendations regarding fusion nuclear data development activities are given below:

Tritium Breeding Related Cross-Sections

(a) ^{7}Li $(n,n'\alpha)$ measurements met the accuracy requirement; new evaluation by Young and Rutherford achieved better than 2% accuracy at 14 MeV and changed very little from 1981 ENDF/B-V.2 analysis.
(b) ^{9}Be $(n,2n)$ and Pb $(n,2n)$ cross-sections still not known with satisfactory accuracy and require more measurements (accuracy 5% or better). Integral measurements are also desirable for data testing.

Total and Differential Cross-Sections for Breeder, Structural, and Shield Materials

(a) Measurement activity is vigorous and results are being employed in new evaluations.
(b) Need more accurate data (10% or better) at energies above 10 MeV.
(c) The implication of data accuracy (differential and gamma-ray production) on nuclear heating (both local and global) needs to be assessed.
(d) Data testing with new evaluations is needed.
(e) Covariance information is needed to assess the uncertainty of evaluated data, particularly for dosimetry cross-sections and for sensitivity and uncertainty analysis of fusion reactor performance.

Activation Cross-Section and Decay Data

(a) Good quality measurements are available for short and medium-term activation cross-sections.
(b) Measurements and evaluations for long-term activation cross-sections are needed (IAEA CRP effort in progress).
(c) Decay data need to be reviewed (in progress for ENDF/B-VI).

Integral Experiment and Analysis for Data Testing

(a) Pure element assemblies are needed for new evaluations.
(b) Fusion relevant, integrated blanket/shield assemblies are needed.
(c) Integral experiments are international in nature:
    — USDOE/JAERI-FNS collaboration on fusion neutronics[32],
    — IAEA benchmark experiment/calculation activity[7].

Fusion Nuclear Data Evaluations

(a) Major progress in ENDF/B-VI, JENDL-3, and EFF-2 is anticipated beginning in 1988.

TABLE 7

Activation Cross-Sections Needed
to be Measured for
Low Activation Fusion Development

Threshold Reactions (13)
^{60}Co (n,p) ^{60}Fe (1.5 × 10^6 y)
^{95}Nb $(n,2n)$ ^{94}Nb (2 × 10^4 y)
^{100}Mo $(n,2n)$ ^{99}Mo ⇒ ^{99}Tc (2.13 × 10^5 y)
^{109}Ag $(n,2n)$ ^{108m}Ag (127 y)
^{151}Eu $(n,2n)$ ^{150m}Eu (35.8 y)
^{153}Eu $(n,2n)$ ^{152}Eu (13.3 y)
^{158}Dy (n,p) ^{158}Tb (150 y)
^{193}Ir $(n,2n)$ ^{192m2}Ir (241 y)
^{182}W $(n,n'\alpha)$ ^{178m2}Hf (31 y)
^{186}W $(n,n'\alpha)$ ^{182} Hf (9 × 10^6 y)
^{187}Re $(n,2n)$ ^{186m}Re (2 × 10^5 y)
^{179}Hf $(n,2n)$ ^{178m2}Hf (31 y)
^{209}Bi $(n,2n)$ ^{208}Bi (3.7 × 10^5 y)
n,γ Reactions (8)
^{62}Ni (n,γ) ^{63}Ni (100 y)
^{58}Ni (n,γ) ^{59}Ni (7.5 × 10^4 y)
^{93}Nb (n,γ) ^{94}Nb (2 × 10^4 y)
^{98}Mo (n,γ) ^{99} Mo ⇒ ^{99}Tc (2.13 × 10^5 y)
^{185}Re (n,γ) ^{186m}Re (2 × 10^5 y)
^{151}Eu (n,γ) ^{152}Eu (13.3 y)
^{165}Ho (n,γ) ^{166m}Ho (1.2 × 10^3 y)
^{191}Ir (n,γ) ^{192m2}Ir (241 y)

(b) An international collaboration effort is strongly recommended to establish a fusion evaluated nuclear data file that is jointly evaluated by the data developers and tested and improved by the data users.

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