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Continuous Energy Cross Section Library for MCNP/MCNPX Based on JENDL High Energy File 2007 -FXJH7-

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The latest JENDL High Energy File (JENDL/HE) was released in 2007 to respond the requirements of reaction data in high energy range up to several GeV to design accelerator facilities such as accelerator-driven systems and research complex like J-PARC. To apply the JENDL/HE-2007 file to the design study, the cross section library of FXJH7 series was constructed from the JENDL/HE file for the calculation using MCNP and MCNPX codes which are widely used in the field of nuclear reactors, fusion reactors, accelerator facilities, medical applications, and so on. In this report, the outline of the JENDL/HE-2007 file, modification of nuclear data processing code NJOY99, construction of FXJH7 library and test calculations for shielding and eigenvalue analyses are summarized.

Keywords: FXJH7, Continuous Energy Cross Section Library, JENDL High Energy File, MCNP, MCNPX, NJOY, Accelerator-driven System, Accelerator Facility

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JENDL 高エネルギーファイル 2007 に基づく MCNP/MCNPX 用連続エネルギー断面積ライブラリ -FXJH7-

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加速器駆動核変換システムや J-PARC などの加速器施設の設計に必要な数 GeV までの核反応データの要求に対し、2007 年版 JENDL 高エネルギーファイル（JENDL/HE-2007）が公開された。そこで、原子炉、核融合炉、加速器施設や医療などの多様な分野で使用されている 3 次元モンテカルロ輸送計算コード MCNP 及び MCNPX 向けの JENDL 高エネルギーファイルに基づく断面積ライブラリ FXJH7 を構築した。本報告書では、2007 年版 JENDL 高エネルギーファイルの概要とそれを処理するための NJOY99 コードの整備、MCNP 用ライブラリ FXJH7 の構築とともに、遮蔽計算・固有値計算によるライブラリ検証結果をまとめた。

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1. Introduction

Requirements for the high energy particle transport analysis with evaluated nuclear data library are increased with the advancement of accelerator applications such as an accelerator-driven system, a spallation neutron source, a radiation therapy, and so on. In actual situation, the analysis related to the above mentioned applications and utilities must use several calculation codes based on different physical analysis schemes. It is desirable to perform the analyses with a consistent and systematic method.

Considering such requirements, evaluation of high energy nuclear data has been performed worldwide. In United States, LA150 cross section library[1)] was released and widely applied for the calculations using MCNPX code[2)]. Other countries in Europe and Asia also promote evaluation of high energy reaction cross sections. In Japan, the first version of JENDL High Energy File (JENDL/HE-2004) [3)] was released in March, 2004. The library includes proton- and neutron-induced reactions data for 66 nuclides in ENDF-6 format in the energy range from 10^{-5} eV to 3 GeV. The draft version of cross section library for MCNPX (FSXJHE1 Library) was built from selected 59 nuclides stored in JENDL/HE-2004. Reflecting the feedback information through a number of benchmark analyses using the FSXJHE1 library, the revised high energy file JENDL/HE-2007[4)] was compiled in December, 2007. The file consists of nuclear data for 106 nuclides adding newly evaluated 40 nuclides including several minor actinides. At this moment, JENDL/HE-2007 is the largest nuclear data file in terms of the number of stored nuclides and the coverage of incident particle energy range. Upcoming final version of JENDL/HE file is planned to include 132 nuclides up to curium isotopes.

In this report, the structure and contents of the continuous energy cross section library FXJH7 series produced from JENDL/HE-2007 are described. Modification of the NJOY99 code[5)] to produce FXJH7 libraries and test calculations of shielding analyses and eigenvalue calculations are also summarized.

2. Structure of JENDL/HE-2007

As experimental cross section data at high energy range are limited, several kinds of evaluation codes were used together with experimental data to construct JENDL/HE-2007. The structure of the JENDL/HE-2007 file is briefly summarized in this chapter.

(1) Neutron Induced Reaction:

Neutron-induced reaction data can be divided into following three energy ranges;

10^{-5} eV to 20 MeV:	Evaluation taken from JENDL-3.3[6)]
20 MeV to E_{inc} MeV:	Evaluation by combining experimental data and (calculated or theoretical) values
E_{inc} MeV to 3 GeV:	Evaluation done by calculation

Note:

The E_{inc} value of each nuclide is different from each other and set in the range from 150 to 250 MeV.

Because the carbon and vanadium isotopes are treated as natural elements in JENDL-3.3, the same data as in JENDL-3.3 are stored for them below 20 MeV.

(2) Proton Induced Reaction:

The proton incidence file can be divided into the following two energy ranges;

E_1 MeV to E_{inc} MeV:	Evaluation by combining experimental data and (calculated or theoretical) values
E_{inc} MeV to 3 GeV:	Evaluation done by calculation

Note:

The values of E_1 and E_{inc} are set according to individual nuclides. E_{inc} is taken in the energy range from 150 to 250 MeV. E_1 is set to a lower energy boundary and in some case, it corresponds to the threshold energy such as 5 MeV for ^{12}C, 1 MeV for ^{56}Fe and ^{208}Pb, etc.

(3) Secondary Particle Production Cross Sections (MT=201 to 207)

For the secondary particle (neutron, gamma, proton, deuteron, triton, ^{3}He and alpha) production cross sections, the JAERI/BNL format which uses MT=201 to 207 to store them is adopted as a standard of JENDL/HE. The LANL format is used to store them together with special identifier called ZAP in MT=5, which corresponds to MT=201 to 207 in the JAERI/BNL format. Because NJOY has been developed and maintained by LANL, the format which can be processed by NJOY99 is only the LANL format with ZAP identifier . The particle production cross section is given above 20 MeV for neutron and whole energy range for proton in the JENDL/HE-2007 file. To process these data correctly by NJOY99, a pre-processing program which converts the JAERI/BNL format to the LANL format was prepared.

(4) Pion Production Cross Sections (MT=208 to 210)

Pion production cross sections are stored with the assignments of MT=208 to 210 in the JENDL/HE-2007 file. The data for pi-plus, pi-zero and pi-minus are assigned to MT=208, 209 and 210 respectively. The threshold energy of pion production cross section is set around 150 MeV. However, they are not included in the present study.

(5) Fission Reaction

In JENDL-3.3, fission cross section (MT=3/MT=18) is provided to the nuclides above thorium (Z=90). Considering high energy fission reaction, it is convenient to store the fission cross sections of the nuclides above tungsten (Z=74) in the JENDL/HE-2007 file. Fission cross section and emitted neutron information (MF=6/MT=18) are provided to neutron- and proton- induced reaction. The number of emitted neutrons (nu-value, MF=1/MT=452) is supplied for neutron-induced fission reaction only.

(6) Treatment of coordinate system

As for coordinate system of energy-angular distribution for secondary particle, the evaluation code GNASH[7)] adopts the center of mass system whereas another evaluation code JAM uses the laboratory system. Because the coordinate system must be unique in current ENDF-6 format, the center of mass system (LAW=1/LANG=2) had been converted into the laboratory system (LAW=7) in JENDL/HE-2007. However, gamma production data are stored with the center of mass system.

3. Modification of NJOY99 Code

To produce cross section library in the ACE format, which is the format for continuous energy cross section library specialized to MCNP and MCNPX, the NJOY code is preferable. Several modifications have been applied to the latest NJOY99 (Version 99.259, distributed in November, 2007) to process the JENDL/HE- 2007 file. The work was done on the PC-Linux environment (SuSE Linux 10.0: kernel 2.6.13) with g77 FORTRAN compiler. Some modifications have been applied to the modules NJOY, RECONR, BROADR, HEATR, THERMR, MODER, ACER, and PURR to process the JENDL/HE-2007 file. Typical modifications are listed in followings.

1) Increase of necessary array size. [BROADR, HEATR, ACER] (Total execution memory size is 95MB).

2) Addition of heating value by energy balance method to set MF=6 type data of kinematical energy [HEATR]

3) Addition of treatments to check the array size to prevent numerical overflow at the processing of LAW=7 type data of angle-energy distribution [ACER]

4) Modification of the treatment when the more than one interpolation modes are assigned to cosines in angle-energy distribution of MF=6/LAW=7 [ACER]

5) Modification of the treatment when the more than one interpolation modes are assigned to particle yields to obtain the threshold energy for particle production in MF=6 [ACER]

6) Correction of the loading procedure with some data page records for particle yields in angle-energy distribution (MF=6/LAW=7) [ACER]

7) Improvement of the search scheme to select the MT number according to incident charged particle [ACER]

8) Addition of the option newfor=2 to keep angle-energy distribution form (LAW=67), because newfor=1 converts laboratory angle-energy law (LAW=67) to continuum energy-angle distribution (LAW=61) [ACER]

9) Correction of the loading procedure with some data page records for angular

distribution (MF=4) [HEATR]

10) Standard number 32 of equal probability bin for angle-energy distribution (MF=6/LAW=7) is extended to 64 to express well the angular distribution of the backward direction in high energy region [ACER]

11) Skip of the treatment of MT=201 to 207 remained in conversion to the LANL format by pre-processing program [ACER]

12) Addition of the treatment of anisotropic angular distribution between 10 and 180 degrees below the possible lower energy in charged particle-induced elastic scattering [ACER]

13) Addition of a treatment of recoil proton in the case of neutron-induced elastic scattering in hydrogen (^{1}H) [ACER]

14) Improvement of the calculation accuracy of μ value from the proton-induced elastic scattering cross section with Legendre form for ^{1}H (LPT=2, MF=6/MT=2/LAW=5) [ACER]

15) Modification of the storage method of angular distribution data and addition of the process of scattering distribution data, in the case of identical charged particle both incident and outgoing particles (MF=6/MT=5/ZAP=1001) [ACER]

16) Neutron yield data in fission reaction (MT=18) use yield data given by tyr=19 prior to the energy-angle distribution (MF=6). [ACER]

17) Modification of to give forcedly the equal probability for isotropic angular scattering in angle-energy distribution (MF=6/LAW=7) of fission reaction (MT=18) [ACER]

18) Modification to keep original number of subsections for compound-particle production reaction as (z, nα) in conversion process from LAW=1/LANG=2 to LAW=7 form (MF=6) [ACER]

4. Construction of Cross Section Library for MCNP and MCNPX

Using modified NJOY99.295, FXJH7 cross section libraries were constructed. FXJH7 libraries are applicable to MCNP5[8] and MCNPX2.5 or later versions. Other older versions of MCNP or MCNPX do not work with FXJH7 libraries because of newly added function such as (1) existence of probability table for unresolved resonance range (ptable), (2) adoption of cumulative angular distribution tables based on newfor=1 format, and (3) application of the new sampling method for charged particle production. Detailed information on nuclides stored in the libraries is summarized in Appendix.

Neutron induced library

Figure 1 illustrates an input data to process neutron induced cross section of ^{238}Pu (MAT=9434) stored in JENDL/HE-2007 by modified NJOY99.259. The flow of the processing modules using unresolved resonance parameter is MODER→RECONR→BROADR→HEATR→THERMR→PURR→ACER. In this sample input, the original ^{238}Pu data are copied to tape20 and then a directory file and an ACE format file are finally written on tape26 and tape27, respectively. In the case of nuclide with no unresolved resonance parameters, process by PURR module is neglected. The basic conditions of NJOY processing for 106 nuclides stored in the JENDL/HE-2007 file are summarized as follows;

Precision of pointwise cross section	0.1%
Temperatures of cross section	20 °C (293.16 °K, 2.526x10^{-8}MeV)
	300 °C (573.16 °K)
	500 °C (773.16 °K)
Upper boundary of thermal energy range	4.6 eV
Treatment of inelastic scattering in thermal energy range	free-gas model
Gamma production data format	detailed format
Unresolved resonance parameter table	Yes (sigma-zero=10^{10}, 10^4, 10^3, 100, 30, 10, 3, 1, 0.1, 10^{-5}), table length=20 (resonance ladders=1000)
newfor option	2 (low67 format)
KERMA calculation method	Energy Balance Method (default)
	Kinematics Method (^{42,46,48}Ca, ^{47}Ti, ^{92,94,95,96,97,98,100}Mo, ^{181}Ta, ^{182,183,184,186}W, ^{206,207,208}Pb, ^{209}Bi)

Using the above mentioned condition, three FXJH7 libraries were constructed. The libraries processed with 20 ℃, 300 ℃ and 500 ℃ are FXJH70N1, FXJH71N1 and FXJH72N1, respectively. The suffix number of each library is 83c, 85c and 87c for ground state nuclides and 84c, 86c and 88c for metastable state nuclide (^{242m}Am). The number of stored nuclides and file size of these libraries are listed as follows;

Library name	Nuclides	File size [Bytes]
FXJH70N1	106	3,277,549,454
FXJH71N1	106	3,255,910,547
FXJH72N1	106	3,246,267,983.

Proton induced library

Figure 2 shows a sample input data to process proton-induced reaction cross section of ^{60}Ni (MAT=2831) by modified NJOY99.259. Flow of the processing modules is MODER → RECONR → ACER. In this sample, the original ^{60}Ni data in JENDL/HE-2007 is copied to tape20 and then a directory file and an ACE format file are finally written on tape26 and tape27, respectively. The basic conditions for cross section processing are as follows;

Precision of pointwise cross section	0.1%
Temperature of cross section	0 °K (0 MeV)
Gamma production data format	detailed format
newfor option	2 (low67 format)

Using this processing condition, FXJH70H1 library for fixed temperature of 0 °K was constructed. Suffix of ZAID for FXJH70H1 is 83h for ground state nuclides and 84h for metastable nuclide (^{242m}Am only). To keep consistency with neutron cross section libraries, FXJH71H1 (ZAID suffix = 85h and 86h) and FXJH72H1 (ZAID suffix = 87h and 88h) were prepared using the same data as FXJH70H1. The number of stored nuclides and file size of these libraries are listed as follows;

Library name	Nuclides	File size [Bytes]
FXJH70H1	106	2,919,458,255
FXJH71H1	106	2,919,458,255
FXJH72H1	106	2,919,458,255

```
moder
20 -21 /
reconr
-21 -22 /
'pendf tape of pu-238 from jendl-he-2007 file' /
9434 2 /
1.000E-03 /
'pu-238 from jendl-he-2007 file' /
'processed by the njoy nuclear data processing system' /
0 /
broadr
-21 -22 -23 /
9434 1 0 0 0 /
1.000E-03 /
293.16 /
0 /
heatr
-21 -23 -24 /
9434 5 0 0 0 2 /
302 318 402 443 444 /
thermr
0 -24 -23 /
0 9434 8 1 1 0 1    221 0 /
293.16 /
1.000E-03 4.6 /
purr
-21 -23 -24 /
9434 1 10 20 1000 /
293.16 /
1.E+10 1.E+4 1000. 100. 30. 10. 3. 1. 0.1 1.E-5 /
0 /
acer
-21 -24 0 26 27 /
1 1 1 .83 /
'pu-238 jendl-he-2007 file (njoy99)' /
9434 293.16 /
2 1 /
/
stop
```

Fig. 1 Sample input data of ^{238}Pu (neutron incident) for modified NJOY99

```
moder
20 -21 /
reconr
-21 -22 /
'pendf tape of ni-60 from jendl-he-2007 file' /
2831 2 /
1.000E-03 /
'ni-60 from jendl-he-2007 file' /
'processed by the njoy nuclear data processing system' /
0 /
acer
-21 -22 0 26 27 /
1 1 1 .83 /
'ni-60 jendl-he-2007 file (njoy99)' /
2831 0.0 /
2 1 /
/
stop
```

Fig. 2 Sample input data of ^{60}Ni (proton incident) for modified NJOY99

5. Data Verification

The test calculations to verify the FXJH7 libraries were performed using MCNPX.

1) WNR experiment[9)]

The secondary neutron angular-energy spectra from thick iron target bombarded by 256 MeV protons were analyzed. Figure 3 summarizes the calculation results using LA150, JENDL/HE-2004 and JENDL/HE-2007. Even JENDL/HE-2007 gives slightly higher values at the energy range below 20 MeV, the result gives good agreement as a whole with the experimental data.

2) TIARA experiment[10)]

The energy spectrum of leaked neutron from 2 m thick concrete shield bombarded by 68MeV p-^{7}Li neutrons were compared with calculation values using LA150, JENDL/HE-2004 and JENDL/HE-2007 as shown in Fig. 4. The results using JENDL/HE-2007 give the similar value with other libraries. Then, it is recognized that there are no significant problems for the construction procedure of FXJH7 library by MCNPX calculation. However, further improvements for JENDL/HE-2007 file are indispensable because there are typical discrepancies compared with experimental data.

3) Criticality experiments by small core[11)]

Eight kinds of experiments for different target fissile nuclides (JEZEBEL-23 and FLATTOP-23 for ^{233}U core, GODIVA and FLATTOP-25 for ^{235}U core, JEZEBEL, JEZEBEL-Pu, FLATTOP-Pu and THOR-Pu for Pu core) were examined. The analyzed results by JENDL/HE-2007 agree well with the calculation results by JENDL-3.3 as shown in Fig.5. In these cases, reflector materials were commonly taken from FSXLIB-J3R2[12)] which is based on JENDL-3.2[13)] because of the existence of materials with natural abundance. This analysis is not essential for the data of additional high energy region but is useful to confirm the validity of NJOY modifications.

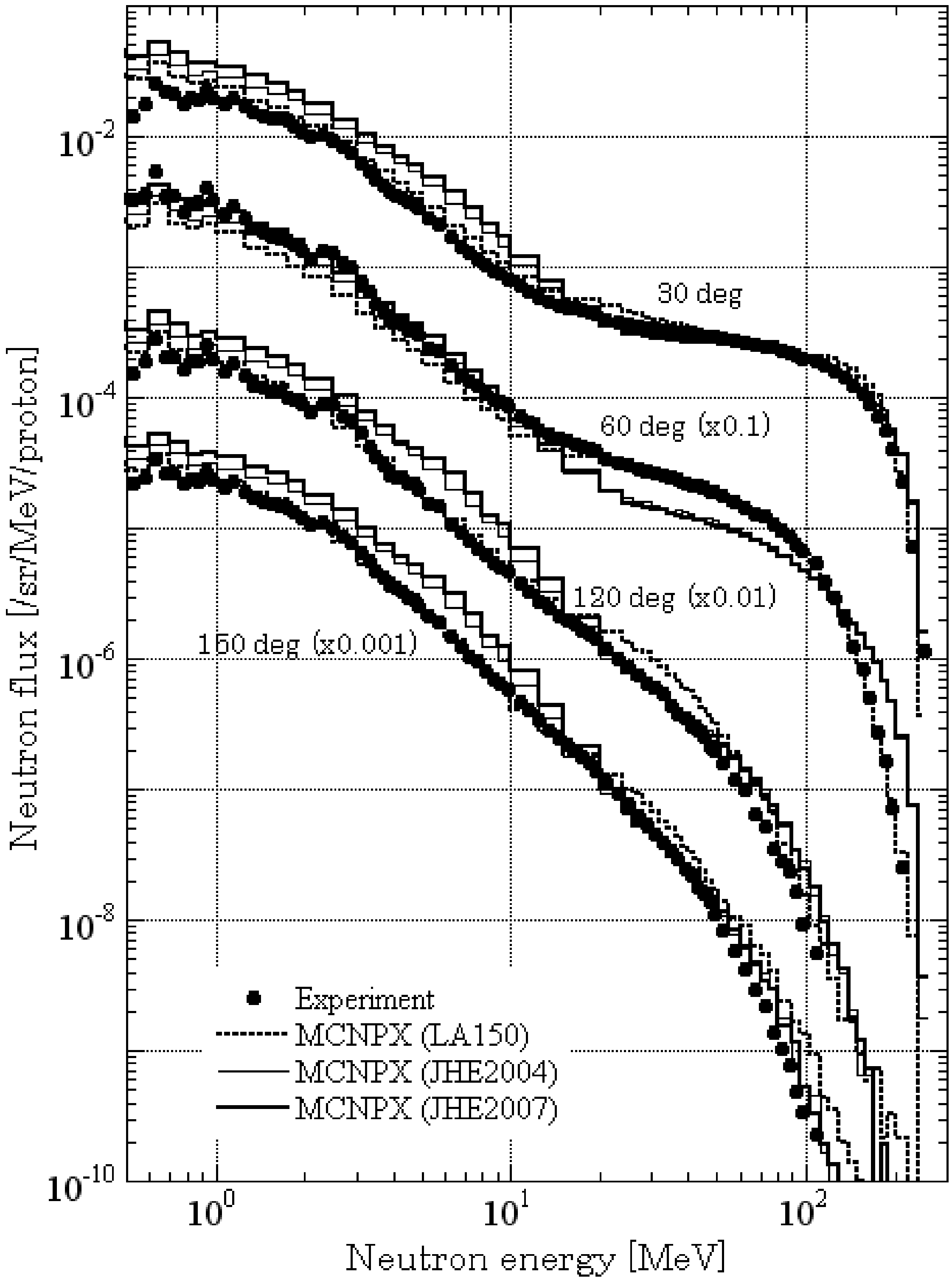

Fig.3 Comparison of neutron yield from iron target bombarded by 256MeV protons

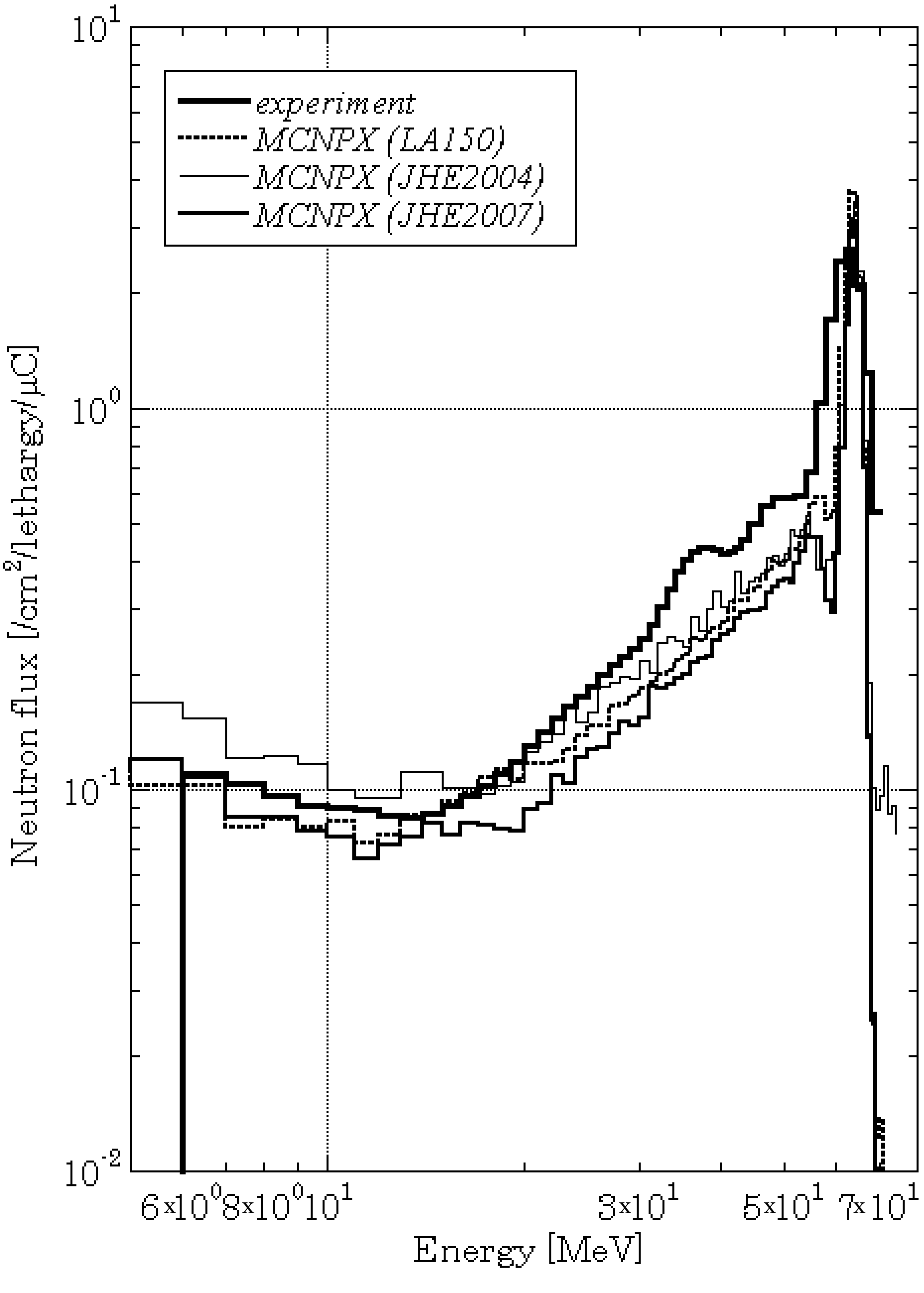

Fig.4 Comparison of neutron spectra on the beam axis behind 2m-thick concrete slab bombarded by 68MeV p-^{7}Li neutron

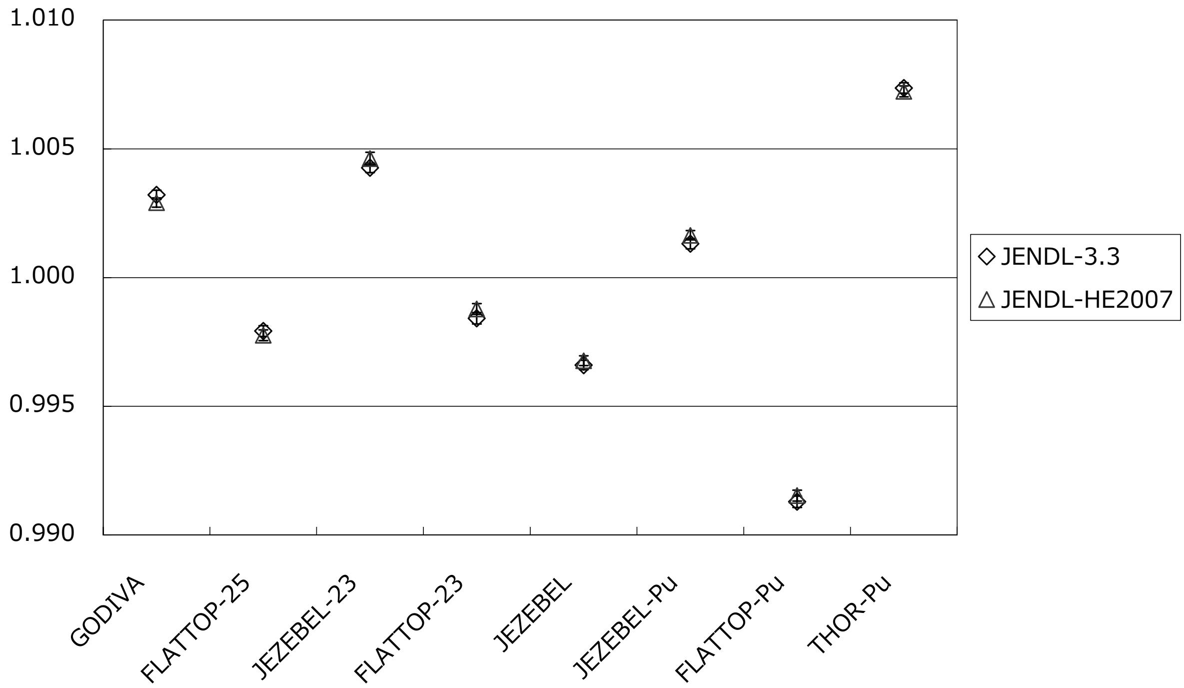

Fig.5 Comparison of analyses result for various small core experiments

6. Summary

Continuous cross section library FSXJH7 was constructed from JENDL/HE-2007. The libraries are prepared for the analysis using the MCNP and MCNPX codes for not only the accelerator related facilities like accelerator-driven system but also the spallation neutron source and the research complex like J-PARC. To perform the analysis in high temperature condition like subcritical core of accelerator-driven system, high energy cross section libraries for 300 ℃ and 500 ℃ were also constructed together with the data for room temperature (20 ℃). Validation of the constructed libraries was performed using several kinds of experimental data by shielding analyses and eigenvalue analyses. From the results of the analyses, it is found that the adequate cross section libraries were produced using modified NJOY.

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Appendix

List of nuclides stored in FXJH7 series library

Following table summarizes the information on each nuclides stored in FXJH7 series library based on JENDL/HE-2007.

ZAID's suffix	Nuclide identifier in ZZZAAA form defined in MCNP manual (ZZZ: atomic number, AAA: mass number) Different suffix denotes the difference of processed temperature and excitation state	
	83	Stable nuclides at 20 ºC
	84	Metastable nuclides at 20 ºC
	85	Stable nuclides at 300 ºC
	86	Metastable nuclides at 300 ºC
	87	Stable nuclides at 500 ºC
	88	Metastable nuclides at 500 ºC
GPD	Existence of gamma production data	
	Blank	No data
	yes	Data stored in whole energy range
	high	Data stored in the energy range above 20 MeV
unresolved	Upper energy boundary of unresolved resonance parameter region (If this value is given, ptable is stored)	
nu data	Specification of number of emitted neutron per fission (ν value)	
	b	stored both total ν and prompt ν
	t	stored total ν only
	p	stored prompt ν only

Table　List of the nuclide name and ZAID in "FXJH7" library based on JENDL/HE-2007

nuclide	ZAID	neutron						proton	
		ZAID's suffix (.*c)			GPD	unresolved E [keV]	nu data	ZAID (.*h) 0K	GPD
		20℃	300℃	500℃					
H-1	1001	83			yes			83	
C-12	6012	83			yes			83	yes
C-13	6013	83			yes			83	yes
N-14	7014	83			yes			83	yes
O-16	8016	83			yes			83	yes
F-19	9019	83	85	87	yes			83	yes
Na-23	11023	83	85	87	yes			83	yes
Mg-24	12024	83	85	87	yes			83	yes
Mg-25	12025	83	85	87	yes			83	yes
Mg-26	12026	83	85	87	yes			83	yes
Al-27	13027	83	85	87	yes			83	yes
Si-28	14028	83	85	87	yes			83	yes
Si-29	14029	83	85	87	yes			83	yes
Si-30	14030	83	85	87	yes			83	yes
Cl-35	17035	83	85	87	high			83	yes
Cl-37	17037	83	85	87	high			83	yes
Ar-36	18036	83	85	87	high			83	yes
Ar-38	18038	83	85	87	high			83	yes
Ar-40	18040	83	85	87	high			83	yes
K-39	19039	83	85	87	yes			83	yes
K-41	19041	83	85	87	yes			83	yes
Ca-40	20040	83	85	87	yes			83	yes
Ca-42	20042	83	85	87	yes			83	yes
Ca-43	20043	83	85	87	yes			83	yes
Ca-44	20044	83	85	87	yes			83	yes
Ca-46	20046	83	85	87	yes			83	yes
Ca-48	20048	83	85	87	yes			83	yes
Ti-46	22046	83	85	87	yes			83	yes
Ti-47	22047	83	85	87	yes			83	yes
Ti-48	22048	83	85	87	yes			83	yes
Ti-49	22049	83	85	87	yes			83	yes
Ti-50	22050	83	85	87	yes			83	yes
V-51	23051	83	85	87	yes			83	yes
Cr-50	24050	83	85	87	yes			83	yes
Cr-52	24052	83	85	87	yes			83	yes
Cr-53	24053	83	85	87	yes			83	yes
Cr-54	24054	83	85	87	yes			83	yes
Mn-55	25055	83	85	87	yes			83	yes
Fe-54	26054	83	85	87	yes			83	yes
Fe-56	26056	83	85	87	yes			83	yes
Fe-57	26057	83	85	87	yes			83	yes
Fe-58	26058	83	85	87	yes			83	yes
Co-59	27059	83	85	87	yes			83	yes
Ni-58	28058	83	85	87	yes			83	yes
Ni-60	28060	83	85	87	yes			83	yes
Ni-61	28061	83	85	87	yes			83	yes
Ni-62	28062	83	85	87	yes			83	yes
Ni-64	28064	83	85	87	yes			83	yes
Cu-63	29063	83	85	87	yes			83	yes
Cu-65	29065	83	85	87	yes			83	yes

Table (continuued)

nuclide	ZAID	neutron						proton	
		ZAID's suffix (.*c)			GPD	unresolved E [keV]	nu data	ZAID (.*h) 0K	GPD
		20℃	300℃	500℃					
Zn−64	30064	83	85	87	high			83	yes
Zn−66	30066	83	85	87	high			83	yes
Zn−67	30067	83	85	87	high			83	yes
Zn−68	30068	83	85	87	high			83	yes
Zn−70	30070	83	85	87	high			83	yes
Ga−69	31069	83	85	87	high			83	yes
Ga−71	31071	83	85	87	high			83	yes
Ge−70	32070	83	85	87	high			83	yes
Ge−72	32072	83	85	87	high			83	yes
Ge−73	32073	83	85	87	high			83	yes
Ge−74	32074	83	85	87	high			83	yes
Ge−76	32076	83	85	87	high			83	yes
As−75	33075	83	85	87	high	100		83	yes
Zr−90	40090	83	85	87	yes			83	yes
Zr−91	40091	83	85	87	yes	100		83	yes
Zr−92	40092	83	85	87	yes	100		83	yes
Zr−94	40094	83	85	87	yes	100		83	yes
Zr−96	40096	83	85	87	yes			83	yes
Nb−93	41093	83	85	87	yes	100		83	yes
Mo−92	42092	83	85	87	yes	100		83	yes
Mo−94	42094	83	85	87	yes	100		83	yes
Mo−95	42095	83	85	87	yes	100		83	yes
Mo−96	42096	83	85	87	yes	100		83	yes
Mo−97	42097	83	85	87	yes	100		83	yes
Mo−98	42098	83	85	87	yes	100		83	yes
Mo−100	42100	83	85	87	yes	100		83	yes
Ta−181	73181	83	85	87	yes	100		83	yes
W−180	74180	83	85	87	yes		t	83	yes
W−182	74182	83	85	87	yes		t	83	yes
W−183	74183	83	85	87	yes		t	83	yes
W−184	74184	83	85	87	yes		t	83	yes
W−186	74186	83	85	87	yes		t	83	yes
Au−197	79197	83	85	87	yes			83	yes
Hg−196	80196	83	85	87	yes		t	83	yes
Hg−198	80198	83	85	87	yes		t	83	yes
Hg−199	80199	83	85	87	yes		t	83	yes
Hg−200	80200	83	85	87	yes		t	83	yes
Hg−201	80201	83	85	87	yes		t	83	yes
Hg−202	80202	83	85	87	yes		t	83	yes
Hg−204	80204	83	85	87	yes		t	83	yes
Pb−204	82204	83	85	87	yes		t	83	yes
Pb−206	82206	83	85	87	yes		t	83	yes
Pb−207	82207	83	85	87	yes		t	83	yes
Pb−208	82208	83	85	87	yes		t	83	yes
Bi−209	83209	83	85	87	yes		t	83	yes
U−235	92235	83	85	87	yes	30	b	83	yes
U−238	92238	83	85	87	yes	150	b	83	yes
Np−237	93237	83	85	87	high	35	b	83	yes
Pu−238	94238	83	85	87	high	44.3	b	83	yes
Pu−239	94239	83	85	87	yes	30	b	83	yes
Pu−240	94240	83	85	87	high	40	b	83	yes
Pu−241	94241	83	85	87	high	30	b	83	yes
Pu−242	94242	83	85	87	high	40	b	83	yes
Am−241	95241	83	85	87	high	40	b	83	yes
Am−242	95242	83	85	87	high	44.3	b	83	yes
Am−242m	95242	84	86	88	high	27.3	b	84	yes

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m-1
密度（質量密度）	キログラム毎立法メートル	kg/m^3
質量体積（比体積）	立法メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
（物質量の）濃度	モル毎立方メートル	mol/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率	（数の）　1	1

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表３．固有の名称とその独自の記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[(a)]	rad		$m \cdot m^{-1}=1$[(b)]
立体角	ステラジアン[(a)]	sr[(c)]		$m^2 \cdot m^{-2}=1$[(b)]
周波数	ヘルツ	Hz		s^{-1}
力	ニュートン	N		$m \cdot kg \cdot s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
エネルギー，仕事，熱量	ジュール	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
工率，放射束	ワット	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
電荷，電気量	クーロン	C		$s \cdot A$
電位差（電圧），起電力	ボルト	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
電気抵抗	オーム	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
磁束	ウエーバ	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
セルシウス温度	セルシウス度[(d)]	℃		K
光束	ルーメン	lm	$cd \cdot sr$[(c)]	$m^2 \cdot m^{-2} \cdot cd=cd$
照度	ルクス	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd=m^{-2} \cdot cd$
（放射性核種の）放射能	ベクレル	Bq		s^{-1}
吸収線量，質量エネルギー分与，カーマ	グレイ	Gy	J/kg	$m^2 \cdot s^{-2}$
線量当量，周辺線量当量，方向性線量当量，個人線量当量，組織線量当	シーベルト	Sv	J/kg	$m^2 \cdot s^{-2}$

(a) ラジアン及びステラジアンの使用は、同じ次元であっても異なった性質をもった量を区別するときの組立単位の表し方として利点がある。組立単位を形作るときのいくつかの用例は表４に示されている。
(b) 実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号“１”は明示されない。
(c) 測光学では、ステラジアンの名称と記号srを単位の表し方の中にそのまま維持している。
(d) この単位は、例としてミリセルシウス度m℃のようにSI接頭語を伴って用いても良い。

表４．単位の中に固有の名称とその独自の記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	$Pa \cdot s$	$m^{-1} \cdot kg \cdot s^{-1}$
力のモーメント	ニュートンメートル	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg \cdot s^{-2}$
角速度	ラジアン毎秒	rad/s	$m \cdot m^{-1} \cdot s^{-1}=s^{-1}$
角加速度	ラジアン毎平方秒	rad/s^2	$m \cdot m^{-1} \cdot s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg \cdot s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
質量熱容量（比熱容量），質量エントロピー	ジュール毎キログラム毎ケルビン	$J/(kg \cdot K)$	$m^2 \cdot s^{-2} \cdot K^{-1}$
質量エネルギー（比エネルギー）	ジュール毎キログラム	J/kg	$m^2 \cdot s^{-2} \cdot K^{-1}$
熱伝導率	ワット毎メートル毎ケルビン	$W/(m \cdot K)$	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1} \cdot kg \cdot s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
体積電荷	クーロン毎立方メートル	C/m^3	$m^{-3} \cdot s \cdot A$
電気変位	クーロン毎平方メートル	C/m^2	$m^{-2} \cdot s \cdot A$
誘電率	ファラド毎メートル	F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
透磁率	ヘンリー毎メートル	H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
モルエントロピー，モル熱容量	ジュール毎モル毎ケルビン	$J/(mol \cdot K)$	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1} \cdot s \cdot A$
吸収線量率	グレイ毎秒	Gy/s	$m^2 \cdot s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4 \cdot m^{-2} \cdot kg \cdot s^{-3}=m^2 \cdot kg \cdot s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2 \cdot sr)$	$m^2 \cdot m^{-2} \cdot kg \cdot s^{-3}=kg \cdot s^{-3}$

表６．国際単位系と併用されるが国際単位系に属さない単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86400 s
度	°	1° =(π/180) rad
分	’	1’ =(1/60)° =(π/10800) rad
秒	”	1” =(1/60)’ =(π/648000) rad
リットル	l、L	$1l=1\ dm^3=10^{-3}m^3$
トン	t	$1t=10^3$ kg
ネーパ	Np	1Np=1
ベル	B	1B=(1/2)ln10(Np)

表７．国際単位系と併用されこれに属さない単位で SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位であらわされる数値
電子ボルト	eV	$1eV=1.60217733(49)\times10^{-19}J$
統一原子質量単位	u	$1u=1.6605402(10)\times10^{-27}kg$
天文単位	ua	$1ua=1.49597870691(30)\times10^{11}m$

表８．国際単位系に属さないが国際単位系と併用されるその他の単位

名称	記号	SI 単位であらわされる数値
海里		1海里=1852m
ノット		1ノット=1海里毎時=(1852/3600)m/s
アール	a	$1\ a=1\ dam^2=10^2m^2$
ヘクタール	ha	$1\ ha=1\ hm^2=10^4m^2$
バール	bar	$1\ bar=0.1MPa=100kPa=1000hPa=10^5Pa$
オングストローム	Å	$1\ Å=0.1nm=10^{-10}m$
バーン	b	$1\ b=100fm^2=10^{-28}m^2$

表９．固有の名称を含むCGS組立単位

名称	記号	SI 単位であらわされる数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn \cdot s/cm^2=0.1Pa \cdot s$
ストークス	St	$1\ St=1cm^2/s=10^{-4}m^2/s$
ガウス	G	$1\ G \triangleq 10^{-4}T$
エルステッド	Oe	$1\ Oe \triangleq (1000/4\pi)A/m$
マクスウェル	Mx	$1\ Mx \triangleq 10^{-8}Wb$
スチルブ	sb	$1\ sb=1cd/cm^2=10^4cd/m^2$
ホト	ph	$1\ ph=10^4lx$
ガル	Gal	$1\ Gal=1cm/s^2=10^{-2}m/s^2$

表10．国際単位に属さないその他の単位の例

名称	記号	SI 単位であらわされる数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R = 2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
X線単位		$1X\ unit=1.002\times10^{-4}nm$
ガンマ	γ	$1\gamma=1\ nT=10^{-9}T$
ジャンスキー	Jy	$1\ Jy=10^{-26}W \cdot m^{-2} \cdot Hz^{-1}$
フェルミ		$1\ fermi=1\ fm=10^{-15}m$
メートル系カラット		$1\ metric\ carat = 200\ mg = 2\times10^{-4}kg$
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	
ミクロン	µ	$1\ \mu=1\mu m=10^{-6}m$

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