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Nuclear Data Needs for Neutron Spectrum Tailoring at International Fusion Materials Irradiation Facility (IFMIF)

Masayoshi SUGIMOTO
Department of Fusion Engineering Research, Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken 319-1195
e-mail: sugimoto@ifmif.tokai.jaeri.go.jp

International Fusion Materials Irradiation Facility (IFMIF) is a proposal of D-Li intense neutron source to cover all aspects of the fusion materials development in the framework of IEA collaboration. The new activity has been started to qualifying the important technical issues called Key Element technology Phase since 2000. Although the neutron spectrum can be adjusted by changing the incident beam energy, it is favorable to be carried out many irradiation tasks at the same time under the unique beam condition. For designing the tailored neutron spectrum, neutron nuclear data for the moderator-reflector materials up to 50 MeV are required. The data for estimating the induced radioactivity is also required to keep the radiation level low enough at maintenance time. The candidate materials and the required accuracy of nuclear data are summarized.

1. Introduction

The development of the fusion reactor materials is one of the most important issues for realizing the fusion power as an energy source. The neutron irradiation tests of the candidate materials are the ultimate and unavoidable steps to obtain the enough qualification and licensing. The IFMIF activity has been carried out for these six years under the framework of IEA international collaboration to construct the intense neutron source for fusion materials irradiation tests. The conceptual design was performed through 1995-1999, which consisted of CDA (Conceptual Design Activity) and CDE (Conceptual Design Evaluation) phases and was completed by a cost reduced design and a facility deployment in three stages (50mA/125mA/250mA for beam current) to contribute to the corresponding stages of the fusion power development [1-3]. After the conceptual design study it is recognized that the several essential technology needs to be verified in a separated activity prior to the engineering test phase by using a prototype system. These key technologies, such as high current and stable beam injector operation, steady and safe Li loop behavior, etc., should be investigated in three-years KEP (Key Element technology verification Phase), so that the proper decision of the next phase, EVP (Engineering Validation Phase), can be made. The updated schedule of IFMIF program is shown in Fig. 1 along with the relation to the DEMO (demonstration reactor for power generation) and ITER (International Thermonuclear Experimental Reactor) schedules.

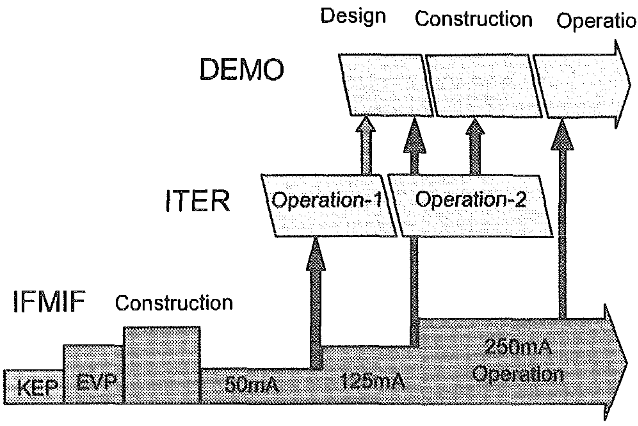

Fig. 1 Staged deployment of IFMIF and relation to DEMO/ITER.

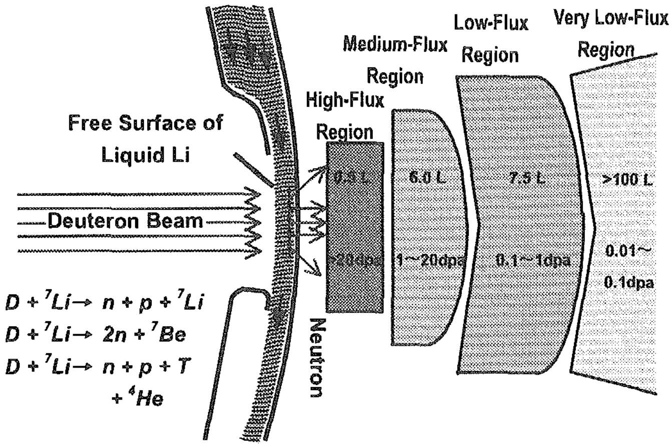

Fig.2 Principle of D-Li neutron source for materials irradiation.

As shown in Fig.2, IFMIF is based on the D-Li neutron source using a high-current deuteron accelerator and a high-speed lithium jet stream target with a free surface on the vacuum side to satisfy the performance requirements (>20dpa for $500cm^3$, see Table 1 in details). The limited irradiation volume is effectively utilized by using a small specimen test technology. The main reaction channels producing the neutrons are the stripping and break up processes having the continuous energy spectrum with a broad peak around the half of incident particle energy in the forward direction, which can be adjusted to the desired energy region suitable for simulating the neutron induced effects in the specific materials. Such a tuning method is powerful to simulate the neutron fields of the various materials at the different locations, like first wall materials, tritium breeding materials or ceramics insulator. The idea of simultaneous irradiation with multiple purposes using a spectrum tailoring method is recently stressed for saving the extra time necessary for the experimental arrangement between the irradiation campaigns [4]. The method employs a small block of spectrum converter (moderator/ reflector/ multiplier) to compromise the intensity and spectrum at the test assemblies in the medium-flux regions. It reduces some part of irradiation volume by sharing the space for the test species and the spectrum converter blocks, so that it is essential to optimize the size and position of the converter to maintain both the neutron flux and the irradiation volume. The present report overviews the possible schemes of spectrum tailoring in IFMIF and the required nuclear data for designing them.

Table 1. Requirements of IFMIF neutron field

Accumulated damage	100~200 dpa (displacement per atom)
Irradiation volume	$>500\ cm^3$ with $10^{14} n/s\ cm^2$
Spatial gradient of neutron flux	<10%/cm
Overall machine availability	70 %

2. Possibility of Spectrum Tailoring

A generic scheme of the arrangement of spectrum converters is shown in Fig. 3, where the test area of the most intense neutron field is almost unchanged and the converter blocks are placed around the area behind to approximate the desired neutron field. The distance between the neutron source and the test cell wall is 1.5 m, however all test assemblies are packed together within 0.5 m from the neutron squrce to achieve the required flux levels. The typical size of converter block would be 5 x 5 x 1 cm^3, made from H, D, Be, O, C, Pb, Bi, U, and other container material elements. The block is necessary to be durable for neutron damage and temperature condition during the irradiation tests. It is also desirable not to produce an excessive radioactivity and decay heat for easy handling after the irradiation tests. The high-energy neutrons are produced in the forward cone of half angle, ~30deg, so that it is effective to place the moderator and multiplier blocks before the spectrum tailored test region. The scattered off neutrons should be reflected back to the test region using the surrounding reflector blocks. If the slower neutron component is desired, the moderator/reflector can be placed behind the test region. The best combination of such converter and reflector blocks in a limited space is a principal design issue to make this method useful.

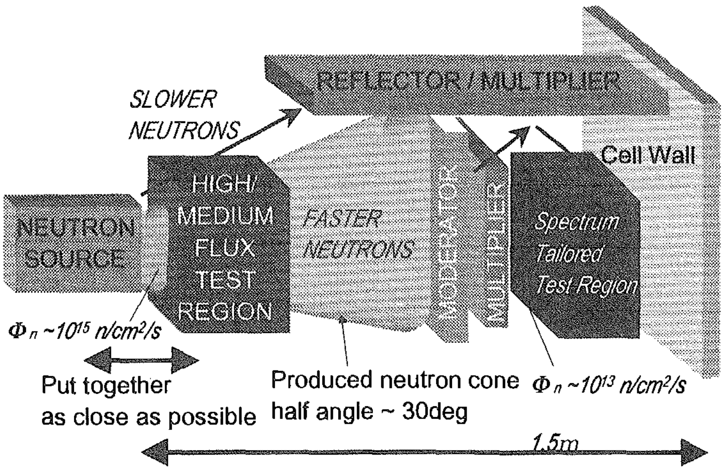

Fig. 3. Schematic configuration of spectrum tailoring in IFMIF

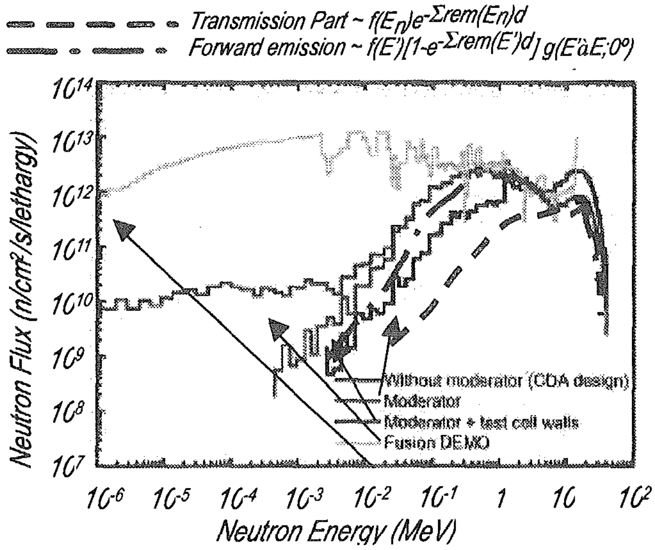

Fig. 4. Comparison of neutron spectra at medium-flux region with/without a Be block after high-flux region (Ref. [4]).

In Fig.4, an example of tailoring is presented to indicate the effectiveness of small piece of spectrum converter. Two Be blocks of 3cm thick are placed before and after the medium flux test region where tritium breeding materials are tested. The original spectrum is mainly modified through the neutron transmission and forward emission by the block close to the target, and the similarity to the fusion reactor spectrum is improved. The lowest energy part can be tailored by using the side reflector blocks as indicated by the calculation including the effect of test cell walls. The drawback of this tailoring method is the reduction of the volume-flux product in the test region, ~50%, so that the best combination of the irradiation test plans for the flux sensitive and spectrum sensitive properties is important. It is helpful to minimize the occupied space if the extremely high density materials can be available for the converter blocks.

3. Nuclear Data Needs

There are two categories to consider the nuclear data needs for the spectrum tailoring: (1) data for neutron transport calculation in the test cell including the test assemblies and converter blocks, and (2) data for nuclear heating and activation calculation in the converter blocks. The issues specific to the IFMIF are the neutron induced reaction data up to 50 MeV and the double differential neutron yield from source reaction. The latter is a basic information for planning every irradiation experiments and the relative accuracy within 10% is required to satisfy the uniformity of neutron flux in the test assemblies.

(1) Neutron Transport Calculation

The Neutron DDX (especially at low energy and larger scattering angles) data are primarily requested to perform the design of spectrum tailoring. The neutron production reaction processes, e.g. (n,2n), (n,3n) and (n,Xn) where X is a charged particle, are important in the considered energy range.

(2) Nuclear Heating Calculation

The photon production and the charged particle production processes are important.

(3) Activation Calculation

The long-lived radioactive residual production process is important. It is necessary to pay much attention to the sequential multi-step reaction process because of the production of the various charged particles and neutrons in the materials.

The above data are generally required also to investigate the other neutronics problems in IFMIF, however the items in (1) are relatively specific to this issue and the present status is overviewed in table 2. Due to the lack of enough experimental data for each nuclear process, a systematical understanding of the partial DDX information becomes important. The integrity of the nuclear process like energy and particle balance is hard to maintain if only the inclusive DDX data are available. The theoretical calculation support for the systematic analyses is inevitable to reduce the modeling parameters. The continued systematical measurements by using 14 MeV (and other neutron source) facilities are highly appreciated to confirm the theoretical approach.

Table 2. Present status of some neutron production reaction channels up to 50 MeV.

Reaction Type	Status
(n,2n)	Generally good situation except for Be, candidate of multiplier material.
(n,3n)	Generally worse. Heavily relied on model calculations. Experimental consistency check is recommended.
(n,pn)	Situation is better. Systematic measurement to separate (n,d) process is lacked.
(n,αn)	Comparatively worse. No systematic study is found.

The "systematics" at the referenced energy (e.g. 14 MeV) may be valuable for practical use, however they contain less physical meaning and it is preferred to apply the following channel excitation approach.

- Analysis of reaction channel branching as a function of excitation energy is fruitful generally.
- Trend of channel branch excitation is dominantly ruled by particle transmission in exit channel and level density form. The compoud nuclear process dominancy is assumed..
- Absolute cross sections of these partial channels are normalized to global trend of non-elastic cross section, which is essentially the size of effective interaction area seen by entering neutron. The optical model calculation is precise, however perspective view is lost easily in the complex process. The simpler approach like Diffraction model (Ramsauer model) is one of the solution.
- Charged particle production near threshold is strongly affected by Coulomb field and "preformed" particle density in the compound nucleus. The latter is generally treated using asymmetry factor, (N-Z)/A.
- Relative DDX data are composed of the phase space factor and the nuclear state factor expressing the contribution of direct and pre-equilibrium process.

The accuracy of cross sections is required to be within 10% for integrated data and 20-40% for the DDX data.

4. Conclusion

The IFMIF project is stepped forward to Key Element Technology Phase in 2000 and a development and design refinement will be carried out for three years. One of the important issues of IFMIF neutronics is achievement of both the high flux/large irradiation volume and the spectrum matching for many purposes. This requires spectrum tailoring and the neutron production DDX up to 50 MeV are required to design the spectrum in a specified region. It is recommended to keep the efforts to measure the experimental data and acquire the precise nuclear response in a systematical way, to achieve the designed neutron field.

Acknowledgement

The IFMIF design concepts are contributed by all members of the IFMIF design team. The supports of Drs. S. Matsuda and M. Seki , and Profs. H. Matsui and T. Muroga are gratefully acknowledged.

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Appendix: Participant List

AKAOSUGI S.	JAERI
AKINO Fujiyoshi	IRM
ANDO Yoshihira	Toshiba Co.
AOKI Takao	Tohoku Univ.
AOYAMA Takafumi	JNC
ARUGA Takeo	JAERI
ASAI Masato	JAERI
ASAMI Akira	
ASAMI Tetsuo	Data Engineering Inc.
ASANO Yoshihiro	JAERI
BABA Mamoru	Tohoku Univ.
Chakrobortty, T.K.	BAEC
CHIBA Satoshi	JAERI
Csikai, Julius	Univ. of Debrecen
Dietze, Klaus	JNC
ENDO Akira	JAERI
FUJIMURA T.	JAERI
FUJITA Mitsutane	NRIM
FUJIWARA Setsuo	JAERI
FUKAHORI Tokio	JAERI
FUKETA Toyojiro	JMSF
FURIHATA Shiori	MRI
FURUTAKA Kazuyoshi	JNC
GOTO Shinichi	JAERI
Guinyun Kim	PAL
HABA Hiromitsu	JAERI
HAGIWARA Masayuki	Tohoku Univ.
HANDA Hiroyuki	HEC
HARADA Hideo	JNC
HARADA Masahide	JAERI
HARIMA Yoshiko	CRC
Harun-ar-Rashid A.K.M.	Univ. of Chittagong
HASEGAWA Akira	JAERI
HINO Tetsushi	Hitachi Ltd.
HIRANO Masami	Nagoya Univ.
HIROISHI Tsutomu	Tohoku Univ.
HORIGUCHI Takayoshi	Hiroshima Int. Univ.
ICHIHARA Akira	JAERI
IGARASI Sin-iti	
IGASHIRA Masayuki	Tokyo Inst. of Tech.
IGUCHI Tetsuo	Nagoya Univ.
IKEDA Kazumi	MHI
IKEUCHI Taketo	Kyushu Univ.
ISHIBASHI Kenji	Kyushu Univ.
ISHII Kazuya	Hitachi Ltd.
ISHIKAWA Makoto	JNC
ISHIMOTO Shunsuke	Kyushu Univ.
IWAMOTO Akira	JAERI
IWAMOTO Osamu	JAERI

IWASAKI Tomohiko	Tohoku Univ.
KAI Tetsuya	JAERI
KASUGAI Yoshimi	JAERI
KATAKURA Jun-ichi	JAERI
KAWADE Kiyoshi	Nagoya Univ.
KAWAI Masayoshi	KEK
KAWANO Toshihiko	Kyushu Univ.
KAWATA Naoki	Tohoku Univ.
Kim Eunjoo	JAERI
KIMOTO Tatsuya	Nuclear Fuel Industries, Ltd.,
KITAZAWA Hideo	NDA
KITSUKI Hirohiko	Kyushu Univ.
KOBAYASHI Katsuhei	Kyoto Univ.
KOMURO Yuichi	JAERI
KONNO Chikara	JAERI
KOORI Norihiko	Tokushima Univ.
KUNIEDA Satosi	Kyushu Univ.
Liem Peng Hong	NAIS
Liu Ping	CIAE
MAEDA Shigetaka	JNC
MAEKAWA Fujio	JAERI
MAEKAWA Hiroshi	JAERI
MAKI Koichi	Hitachi Ltd.
MARUYAMA Tomoyuki	Nihon Univ.
MATSUNOBU Hiroyuki	DEI
MEIGO Shin-ichiro	JAERI
MINEMOTO K.	VIC
MIURA Takako	Tohoku Univ.
MUKAIYAMA Takehiko	JAERI
MURATA Isao	Osaka Univ.
MURATA Toru	AITEL
Nada Mamada	Nagoya Univ.
NAGAME Yuichiro	JAERI
NAITO Yoshitaka	NAIS
NAKAGAWA Tsuneo	JAERI
NAKAJIMA Ken	JAERI
NAKAMURA Hisashi	
NAKAMURA Shoji	JNC
NAKAMURA Takashi	Tohoku Univ.
NAKAMURA Takeshi	KCC
NAKASHIMA Hiroshi	JAERI
NAUCHI Yasushi	CRIEPI
NEMOTO Makoto	VIC
NISHINAKA Ichiro	JAERI
NISHIO Katsuhisa	JAERI
NISHIO Takashi	Osaka Univ.
NISHITANI Takeo	JAERI
NODA Tetsuji	NRIM
OCHIAI Kentaro	JAERI

OCHIAI Masaaki	JAERI
ODANO Naoteru	JAERI
OHBAYASI Yosihide	Hokkaido Univ.
OHKAWACHI Yasushi	JNC
OHKUBO Makio	SOHONRR
OHSAWA Takaaki	Kinki Univ.
OIGAWA Hiroyuki	JAERI
OKAJIMA Shigeaki	JAERI
OKUNO Hiroshi	JAERI
OYAMATSU Kazuhiro	Aichi Shukutoku Univ.
OZAWA Akira	RIKEN
P. Siangsanan	OAEP
Rong Jian	JAERI
SAIHO Fuminobu	Kyushu Univ.
SAKAMOTO Koh	Kanazawa Univ.
SAKAMOTO Yukio	JAERI
SAKURAI Kiyoshi	JAERI
Sam Yol Lee	Kyoto Univ.
SASAKI Kenji	ARTECH
SASAKI Michiya	Tohoku Univ.
SATO Hisaki	Tohoku Univ.
SATOH Daiki	Kyushu Univ.
SENGOKU Seio	JAERI
Sergey G. Yavshits	KRI
SHIGYO Nobuhiro	Kyushu Univ.
SHIKAZONO Naomoto	IRM
SHIMADA Shoichiro	JAERI
SHIMIZU Toshiaki	Nagoya Univ.
SHONO Akira	JNC
SUGI Teruo	JAERI
SUGIMOTO Masayoshi	JAERI
Sun Weili	Kyushu Univ.
TABUCHI Shiro	JNC
TAHARA Yoshihisa	MHI
TAJI Y.	RIST
TAKADA Hiroshi	JAERI
TAKADA Naoyuki	Nuclear Fuel Industries, Ltd.,
TAKANO Hideki	JAERI
TERADA Yasuaki	Osaka Univ.
TOITA Sentaro	JAERI
TSUJI Masatoshi	TEC
TSUKADA Kazuaki	JAERI
UNO Yoshitomo	JAERI
USUDA Shigekazu	JAERI
WATANABE Yukinobu	Kyushu Univ.
YAMABAYASHI Hisamichi	CTC
YAMAGUCHI Yasuhiro	JAERI
YAMAMOTO Toru	NUPEC
YAMANO Naoki	SAE
Yang Jin An	NAIS
YASHIMA Hiroshi	Tohoku Univ.
YATABE	NAIS
YOSHIDA Tadashi	Musashi Inst. of Tech.
YOSHIZAWA Nobuaki	MRI
ZUKERAN Atsushi	Hitachi Ltd.

国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	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
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 3　固有の名称をもつ SI 組立単位

量	名称	記号	他の SI 単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	m·kg/s^2
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 2　SI と併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV = 1.60218×10^{-19} J

1 u = 1.66054×10^{-27} kg

表 4　SI と共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å = 0.1 nm = 10^{-10} m

1 b = 100 fm^2 = 10^{-28} m^2

1 bar = 0.1 MPa = 10^5 Pa

1 Gal = 1 cm/s^2 = 10^{-2} m/s^2

1 Ci = 3.7×10^{10} Bq

1 R = 2.58×10^{-4} C/kg

1 rad = 1 cGy = 10^{-2} Gy

1 rem = 1 cSv = 10^{-2} Sv

表 5　SI 接頭語

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

（注）

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および 1 u の値は CODATA の1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JIS では流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC 閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表2のカテゴリーに入れている。

換算表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s(N·s/m^2) = 10 P(ポアズ)(g/(cm·s))

動粘度　1 m^2/s = 10^4St(ストークス)(cm^2/s)

圧	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
力	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J（計量法）
　= 4.184 J　（熱化学）
　= 4.1855 J　（15 °C）
　= 4.1868 J（国際蒸気表）

仕事率　1 PS（仏馬力）
　= 75 kgf·m/s
　= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）