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Information Exchange on HTGR and Nuclear Hydrogen Technology between JAEA and INET in 2009

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The worldwide interests in the HTGR (High Temperature Gas-cooled Reactor) have been growing because the high temperature heat produced by the reactor can be utilized not only for efficient power generation but also for broad process heat applications, especially for thermo-chemical hydrogen production to fuel a prospective hydrogen economy in future. Presently only two HTGR reactors are operational in the world, including the HTTR (High Temperature Engineering Test Reactor) in Japan Atomic Energy Agency (JAEA) and the HTR-10 in the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University in China. JAEA and INET have cooperated since 1986 in the field of HTGR development, particularly on the HTTR and HTR-10 projects. This report describes the cooperation activities on HTGR and nuclear hydrogen technology between JAEA and INET in 2009.

Keywords: HTGR, HTTR, HTR-10, International Cooperation

* Institute of Nuclear and New Energy Technology of Tsinghua University

日本原子力研究開発機構と中国清華大学核能及新能源技術研究院との
高温ガス炉及び原子力水素製造技術の情報交換に関する報告書（2009 年）

日本原子力研究開発機構大洗研究開発センター高温工学試験研究炉部
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高温ガス炉から取り出される高温の熱は、高効率発電のみならず、広範囲なプロセス熱利用、特に、熱化学水素製造に用いることができることから、高温ガス炉への関心が世界的に高まっている。現在、世界で運転されている高温ガス炉は２基のみで、１つが独立行政法人日本原子力研究開発機構の HTTR（高温工学試験研究炉）であり、もう 1 つが、中国の清華大学核能及新能源技術研究院（INET）の HTR-10 である。原子力機構と INET は、1986 年の覚書締結以来、これまで高温ガス炉分野、特に、HTTR 計画及び HTR-10 計画について研究協力を進めてきた。本報は、2009 年の原子力機構と INET の高温ガス炉及び原子力水素製造技術開発に関する研究協力活動についてまとめたものである。

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1. Introduction

The worldwide interests in the HTGR (High Temperature Gas-cooled Reactor) have been growing because the high temperature heat produced by the reactor can be utilized not only for efficient power generation but also for broad process heat applications, especially for thermo-chemical hydrogen production to fuel a prospective hydrogen economy in future. National projects on HTGRs are ongoing in Japan, China, USA, South Africa, Korea, etc., and the VHTR (Very High-Temperature Reactor) is chosen as the most promising Generation IV nuclear reactor system in GIF (Generation IV International Forum). There are presently only two HTGRs operating in the world, HTTR, High Temperature Engineering Test Reactor, in JAEA (see Table 1.1 and Fig. 1.1) and HTR-10 in Institute of Nuclear and New Energy Technology of Tsinghua University (INET) (see Table 1.2 and Fig. 1.2).

Construction of the HTTR was started in 1991 and its first criticality was achieved on November 10, 1998. Then, power-up tests were carried out, and rated thermal power of 30MW at the reactor outlet coolant temperature of 850°C was attained in December 2001. Rated power operation and safety demonstration tests using the HTTR have been conducted since FY2002. After several operational cycles, high temperature test operation of the HTTR to achieve the coolant temperature of 950°C was conducted, and coolant temperature of 950°C at reactor outlet was reached on April 14, 2004.

First criticality of the HTR-10 was achieved at air condition on December 1, 2000, and re-criticality at helium condition was attained in July 2002. Then, power-up tests were conducted, and the first synchronization at 3MWt was achieved in January 2003, followed by full power operation at 10MWt with core outlet temperature of 700°C in February 2003. Safety demonstration tests including helium circulator trip without scram and reactivity insertion without scram were carried out in 2003 and 2005.

INET is also promoting development of Modular High-Temperature Gas-cooled Reactor (MHTGR) named as High Temperature Gas-Cooled Reactor – Pebble bed Module (HTR-PM) (see Table 1.2 and Fig. 1.2), based on the technology and experiences of the HTR-10. The HTR-PM project is under the standard design phase, and the HTR-PM demonstration plant is planned to finish construction by 2013.

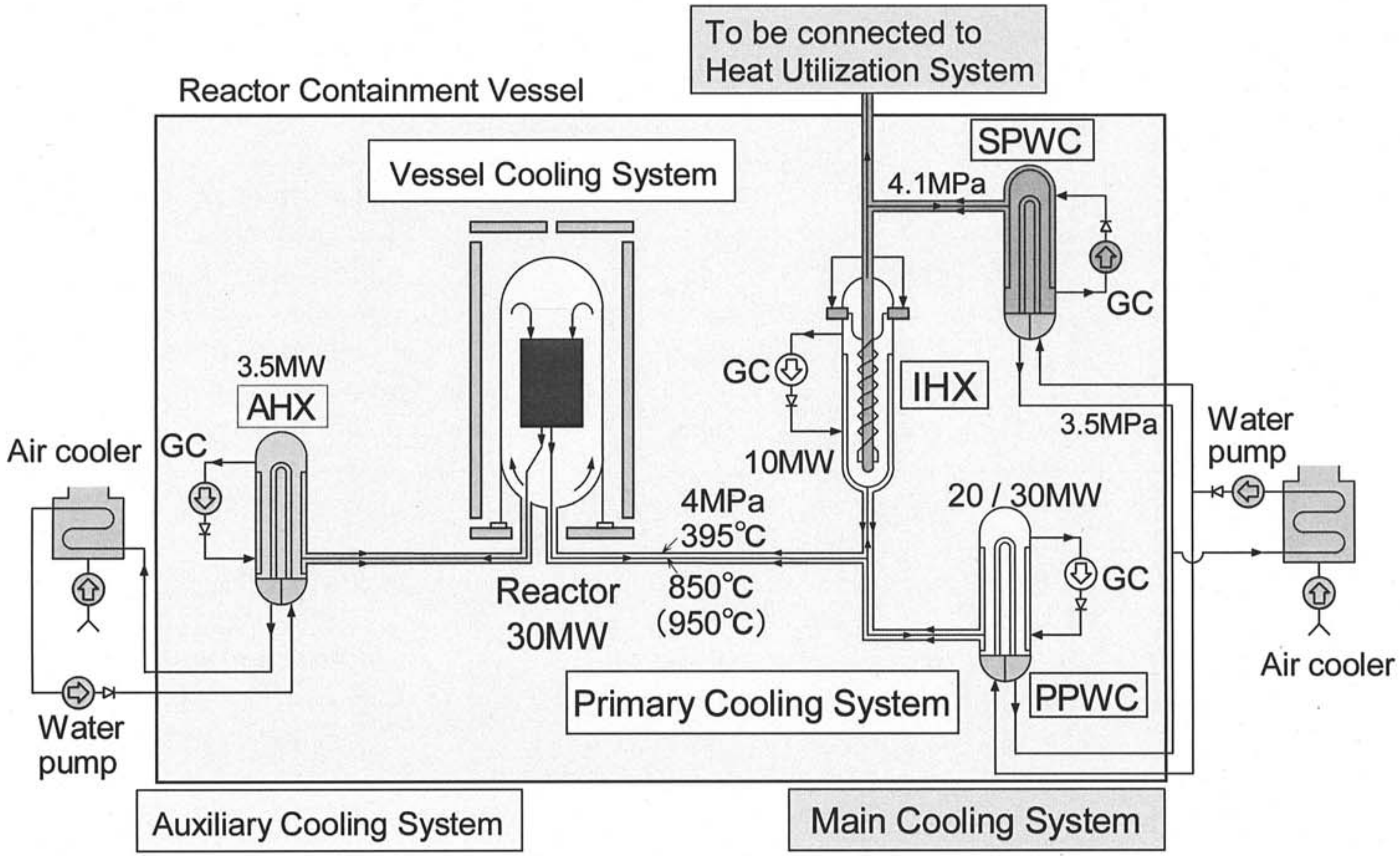
JAEA and INET have cooperated in the area of HTGR development, especially on HTTR and HTR-10 projects, since 1986 when a Memorandum of Understanding was exchanged between the two institutes. This report describes cooperation on HTGR development between JAEA and INET and major cooperation activities in 2009.

Table 1.1 Major specifications of HTTR

Thermal power	30MW
Outlet coolant temperature	850°C/950°C
Inlet coolant temperature	395°C
Fuel	Low enriched UO_2
Fuel element type	Prismatic block
Direction of coolant flow	Downward
Pressure vessel	Steel
Number of cooling loop	1
Heat removal	IHX and PPWC (parallel loaded)
Primary coolant pressure	4MPa
Containment type	Steel containment
Plant lifetime	20 years

Table 1.2 Specifications of HTR-10 and HTR-PM

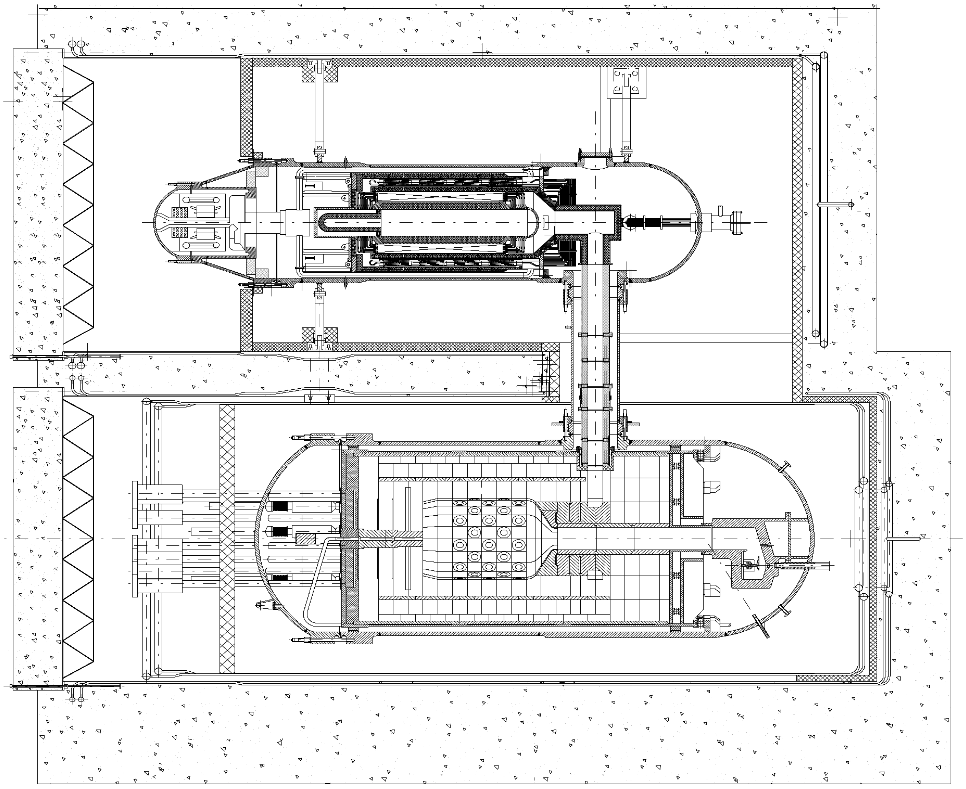
Parameters		HTR-10	HTR-PM
Reactor thermal power	MW	10	250
Net output power	MW	2.5	100
Primary helium pressure	MPa	3.0	7.0
Helium inlet temperature	°C	250	250
Helium outlet temperature	°C	700	750
Helium mass flow rate	kg/s	4.3	96
Main steam pressure	MPa	3.5	13.5
Main steam temperature	°C	435	543
Number of spherical fuel elements	-	27000	380000



IHX : Intermediate heat exchanger
PPWC: Primary pressurized water cooler
SPWC: Secondary pressurized water cooler
AHX : Auxiliary heat exchanger
GC : Gas circulator

Fig. 1.1 Cooling system of HTTR

HTR-10



HTR-PM

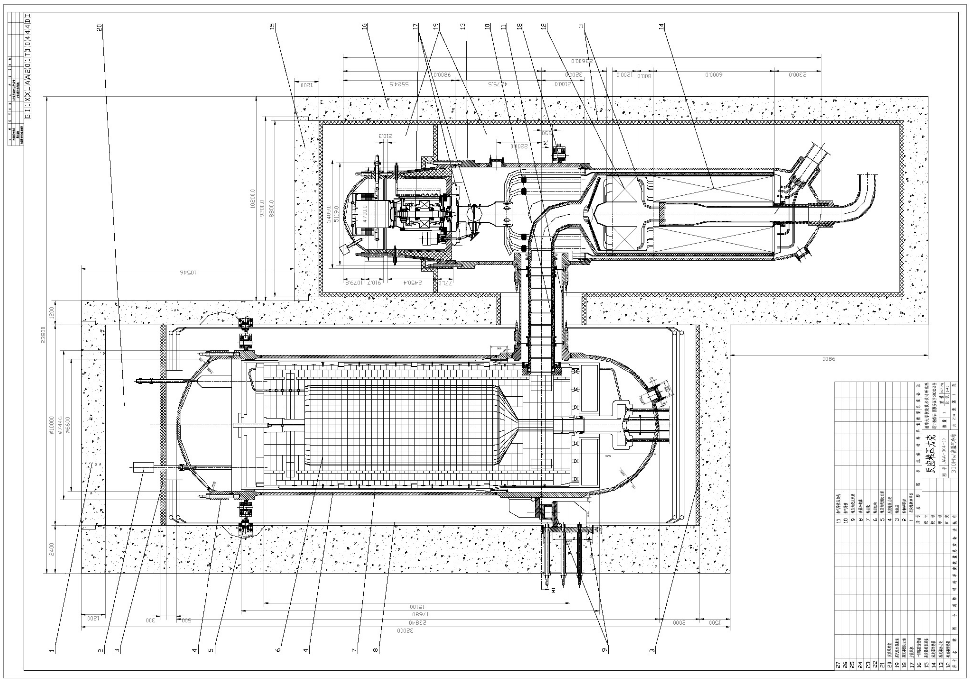


Fig. 1.2 Figures of HTR-10 and HTR-PM

2. Cooperation on HTGR Development between JAEA and INET

2.1 History of Cooperation

Vice chairman of Atomic Energy Commission of Japan, was requested for collaboration between China and Japan in the area of HTGR research and development during his visit to China in June 1985.

In September 1985, Director of Institute of Nuclear Energy Technology of Tsinghua University (INET) visited HTGR research and development facilities in Japan Atomic Energy Research Institute (JAERI), and discussed exchange of a Memorandum of Understanding (MOU) about cooperation on HTGR research and development.

In December 1985, A JAERI delegation visited INET and discussed exchange of a MOU.

In June 1986, JAERI and INET exchanged the initial MOU.

In June 1988, valid duration of the MOU was extended until June 1990.

In June 1990, the MOU was further extended until June 1995. In addition, Personnel Assignment Agreement was added to the memorandum of understanding.

In June 1995, valid duration of the MOU was extended until June 2000.

In June 2000, the MOU was further extended until June 2005.

In September 2003, Institute of Nuclear Energy Technology of Tsinghua University (INET) changed its full official name to Institute of Nuclear and New Energy Technology of Tsinghua University (INET) to further broaden academic disciplines of the institute.

In June 2005, valid duration of the MOU was once again extended until June 2010.

In October 2005, JAERI and Japan Nuclear Cycle Development Institute (JNC) merged to form Japan Atomic Energy Agency (JAEA).

Since June 1986 until today, information exchange meetings have been held almost every year as shown in Table 2.1, and general information exchange on research and development plan on HTTR and HTR-10 as well as on technologies in the area of HTGRs has been made.

Since the HTR-10 is the only pebble bed type HTGR and the HTTR the only prismatic block type HTGR being operated in the world at present, the information exchange has been beneficial for both JAEA and INET.

Since 1990 when the Personnel Assignment Agreement was added, JAEA has accepted researchers from INET in the field of HTGR safety, nuclear heat utilization, etc.

2.2 Area of Cooperation

The original MOU exchanged in 1986 stipulated the area of cooperation as follows. INET and

JAEA will provide to each other program status and technical outline information such as is generally available at each of their respective facilities relating to their respective programs for research and development of Gas-cooled Reactors. Each party will review the information provided by the other's programs as a basis for discussions on a future agreement. The subject matter of the information to be exchanged shall include, but not be limited to, the followings:

A) The High-Temperature Gas-cooled Reactor (HTGR), for process heat and cogeneration, including both fuel technology and plant technology.
B) The Very-High Temperature Gas-cooled Reactor (VHTR), for process heat, including both fuel technology and plant technology.
C) (Note: The Very-High Temperature Gas-cooled Reactor (VHTR) here is similar to but not the same as the VHTR selected as a Generation IV nuclear system. The process heat application includes nuclear hydrogen production.)

In 1990, the MOU was amended by inserting that each party may assign its personnel into the facility of the other in accordance with the Personnel Assignment Agreement, and that for the purpose of carrying out the cooperative activities under the MOU, both parties may exchange samples when agreed by both of them. The MOU in 1990 also added a new paragraph: Each party shall make available, at least once a year to the other party reports written in English which have been published by each party.

2.3 Status of HTTR in 2009

In January 2009, HTTR started pre-operational tests of the facility. In the tests, small degradation of gasket in the closure of a standpipe which was located at the top of the reactor pressure vessel. The operation was postponed and a replacement of the gasket was carried out.

In March 2009, pre-operational tests were started again. In the tests, small depressurization was found in the secondary helium circuit. In the investigation, degradation of gaskets at the upper and middle flange of the secondary helium gas circulator.

The replacement work of the gasket in the upper flange was carried out at April. The replacement work of the gasket in the middle flange was carried out in August. To confirm the leak tightness of the secondary helium circuit and other cooling circuit, the HTTR cooling system was operated after the replacement works. The leak tightness of all cooling circuits were confirmed through the operation. During the operation, cold tests of loss of core flow tests and loss of core cooling tests, which will be started in 2010, were carried out to obtain data for pre-evaluation of the tests.

The HTTR was started up at December 2009 for periodical inspection. At the operation, control rod worth, excess reactivity, shutdown margin, etc. were measured and the reactor was shut down.

On January 2009, the HTTR was started up again to pass the periodical inspection and to achieve 50 days full power operation in high temperature test operation mode (about 950 ^{o}C of outlet coolant temperature). The long term high temperature operation will finish in March, 2010.

After the 50 days full power operation, test operation to obtain burnup characteristics such as temperature coefficients, fuel performance, etc. and new safety demonstration tests such as loss of core flow tests (all primary gas circulator stop tests) and loss of core cooling tests (all primary gas circulator stop with vessel cooling system stop tests) will be started.

2.4 Status of HTR-10 in 2009

In the year of 2009, the main efforts involved in HTR-10 were made focusing on the preparation of a demonstration test of the passive residual heat removal system (PRHRS), training of operators for HTR-PM project. In the meanwhile, the regular maintenance and check in HTR-10 were conducted including system enhancement and equipment maintenance, regular check and experiment, etc., but no power operation was carried out.

A demonstration test of the passive residual heat removal system (PRHRS) in HTR-10 was scheduled to verify and improve the PRHRS design for HTR-PM. The preparation for the test was carried out in 2009. The necessary measurement sensors and devices were installed. The preparation did not affect its safety function.

In the process of system enhancement and equipment maintenance, analysis and research were made concerning essentially with reducing potential equipment failures. Accordingly, design optimization, technical upgrading, and equipment maintenance were carried out to make sure that HTR-10 will run under stable, reliable and safe conditions to ensure important experiments to be carried out.

Regular check and tests were carried out during the shutdown period to ensure the reliability and safety of operation of HTR-10, in accordance with the Regulations for Periodical Tests and Examinations, and in line with the frequency and requirements prescribed in HTR-10 Technical Specifications.

In 2009, the training program for operating staff is focused on the training of active operators for HTR-PM and maintenance personnel for HTR-10, and the training for license application or renewal.

Table 2.1 Number of people visiting INET from JAEA and JAEA from INET for the purpose of exchanging information on HTGR

Year	Number of people visiting INET from JAEA	Number of people visiting JAEA from INET
1986	2	0
1987	2	0
1988	1	2
1989	0	1
1990	1	3
1991	3	0
1992	2	2
1993	1	4
1994	3	1
1995	2	2
1996	1	4
1997	2	2
1998	4	2
1999	0	3
2000	3	2
2001	0	2
2002	1	2
2003	1	3
2004	2	5
2005	5	3
2006	1	3
2007	2	5
2008	1	0
2009	0	0

3. Major Cooperation Activities in 2009

3.1 Extension of MOU

The present MOU will be expired in June 2010. The future of the MOU was discussed both JAEA and INET. JAEA and INET agreed to extend the MOU until June 2015 without revision of the contents of the MOU except the period of MOU. The procedure for extension of MOU is now proceeding in both side.

3.2 Mutual Visits between JAEA and INET

There is no visit between JAEA and INET during the year 2009. Information on present status of the HTTR and HTR-10, etc. was exchanged by e-mail.

4. Concluding Remarks

This report summarized cooperation on HTGR development between JAEA and INET and major cooperation activities in 2009. The MOU between JAEA and INET is extended for five years. Enhancing future collaboration between JAEA and INET is important, and continuous information exchange on HTGR-related technologies is beneficial for the both institutes.

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	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方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
量濃度(a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立法メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率(b)	（数字の） 1	1
比透磁率(b)	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表される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(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^{2}/m^2
周波数	ヘルツ(d)	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	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト(g)	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。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である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含む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 s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ sA$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
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 K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（X線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ sA$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

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６．SIに属さないが、SIと併用される単位

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=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	$1ha=1hm^2=10^4m^2$
リットル	L，l	$1L=1l=1dm^3=10^3cm^3=10^{-3}m^3$
トン	t	$1t=10^3\ kg$

表７．SIに属さないが、SIと併用される単位で、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 単位で表される数値
電子ボルト	eV	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$1ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1MPa=100kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	$1\ Å=0.1nm=100pm=10^{-10}m$
海里	M	1 M=1852m
バーン	b	$1\ b=100fm^2=(10^{-12}cm)2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s$
ストークス	St	$1\ St\ =1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	$1\ sb\ =1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx$
ガル	Gal	$1\ Gal\ =1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウェル	Mx	$1\ Mx = 1G\ cm^2=10^{-8}Wb$
ガウス	G	$1\ G\ =1Mx\ cm^{-2}\ =10^{-4}T$
エルステッド(c)	Oe	$1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}$

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
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	$1\ rem=1\ cSv=10^{-2}Sv$
ガンマ	γ	1 γ =1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
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	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ \mu\ =1\mu m=10^{-6}m$

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