JAEA-Review
2010-049

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November 2010
Japan Atomic Energy Agency
日本原子力研究開発機構

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(Received September 9, 2010)

The hot laboratory (JMTR-HL) was founded to examine the objects mainly irradiated in the JMTR(Japan Materials Testing Reactor), and has been operated since 1971. The JMTR has been stopped from FY2006 for the refurbishment and will be re-started from FY2011. The post irradiation examination for high burn up fuels and large specimen will be carried out in the restarted JMTR. The JMTR-HL plans to put a three dimensional X-ray Computerized Tomography (CT) inspection system in place until the restart of JMTR in order to satisfy the requirement of valuable irradiation data for safety and plant life time management of nuclear power plants in the future. The three dimensional X-ray CT inspection system is able to observe a defect geometry closely and visually compared with a two dimensional system.

In this paper, system design, production, installation and performance tests of an X-ray CT inspection system in a hot cell are reported. The X-ray CT inspection system consists of a computed tomography scanner, an X-ray source, a movable sample positioned, an X-ray detector, a collimator, and so on. After installation of apparatus, performance tests using irradiated fuel rods and radioisotopes were carried out to confirm the influence of gamma rays and transmission X-ray property.

By this development of the X-ray CT inspection system, it became possible to provide data with high technical value for post irradiation examination of high burn-up fuels and large type specimens.

Keywords: JMTR, Testing Reactor, Refurbishment, Nondestructive Testing, Three Dimensional, X-ray CT Inspection

三次元X線撮影装置による非破壊検査

日本原子力研究開発機構　大洗研究開発センター
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(2010 年　9 月　9 日　受理)

材料試験炉(JMTR)のホットラボ施設（JMTR-HL）は、主に JMTR で照射した照射物を試験するために設置され、1971 年から運転を行ってきた。JMTR は 2006 年 8 月に、改修のために停止し、2011 年より再稼働する計画である。再稼働後の JMTR では、高燃焼度燃料及び大型試験片の照射試験が計画されている。JMTR-HL は、今後の発電炉の安全性とプラント寿命管理に関わる技術的価値の高い照射データの要求を満たすため、三次元 X 線撮影装置をホットセル内に整備した。三次元 X 線撮影装置は、従来の二次元のものに比べて欠陥形状を、視覚的にかつ細かく観察する利点を有している。

三次元 X 線撮影装置は、CT スキャナ、X 線発生部、回転昇降試料台、X 線検出器、コリメータ等から構成される。本報告では、三次元 X 線撮影装置のシステム設計、製作、ホットセルへの設置及びγ線の影響やX線の透過性能を調べるために、照射済燃料棒やＲＩを用いたホット性能試験について述べる。

この三次元 X 線撮影装置の整備により、高燃焼度燃料や大型試験片の照射後試験において技術的価値の高いデータを供給することができるようになった。

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1. Introduction

The X-ray Computerized Tomography (CT) inspection method is widely used in the medical field and the engineering field. Especially, it is used in medical treatment field to know the size of malfunction parts of the human body and detail information at the position.

In the nuclear engineering field, X-ray radiography has been performed for the observation of arrangement of fuel pellets in fuel rods. But this method provides only the information of positions of pellets in fuel rods before irradiation and after irradiation. It is not possible to observe detail information inside them by this method.

In this paper, system design, production, installation and performance tests of a three dimensional X-ray CT inspection system in a hot cell are reported.

We performed investigations of the appropriate position of apparatus, the effect of gamma rays from irradiated fuel rods, and the method to treat irradiated fuel rods by remote operation for the development of X-ray CT inspection system.

After installation of apparatus, performance tests using irradiated fuel rods and radioisotopes were carried out to confirm the influence of gamma rays and transmission X-ray property.

By this development of the X-ray CT inspection system, it is possible to provide data with high technical value for post irradiation examination of high burn-up fuels and large type specimens.

2. Hot laboratory

The Japan Materials Testing Reactor (JMTR) is the largest scale materials testing reactor with a thermal power of 50MW. It is a testing reactor dedicated to the irradiation tests of materials and fuels. The JMTR hot laboratory was put into service in 1971 to perform post irradiation examinations for specimens irradiated mainly in JMTR and various post irradiation examinations on nuclear fuels and materials, reactor core components and other materials are carried out.

The concrete cell in the hot laboratory is connected with the reactor by the water canal. Hence irradiated radioactive capsules or specimens are safely transferred under water through the canal.

There are three trains of β-γ cells, i.e. 8 concrete cells attached with 4 microscope lead cells, 7 lead cells and 5 steel cells in hot laboratory and all operations for irradiated specimens are performed remotely through the shielding glass by manipulators. Figure 1 shows schematic drawing of the hot laboratory.

The X-ray CT inspection system was installed in concrete cell No.3 in the JMTR Hot laboratory. In this cell, an X-ray radiography apparatus had been installed for nondestructive tests of irradiated fuel rods and irradiation capsules for about 40 years. This cell is designed for X-ray radiography and hence high voltage cable holes, remote control signal cable holes and cooling pipes are installed. These are reused after dismantling of X-ray radiography apparatus. In this cell, gamma scanning apparatus have been installed for nondestructive tests. CT tests and gamma scanning tests adjust the schedule and are performed.

3. An outline of the X-ray CT inspection system

Figure 2 shows schematic drawing of the X-ray CT inspection system and table 1 shows specifications. This system consists of an X-ray generator, an X-ray detector, mechanics for moving specimens, a control board and a data processing unit.

We adopt third generation X-ray CT method for our system[1)]. It is main stream of X-ray CT scan. Figure 3 shows difference of scanning method among generations. In our system, X-ray detectors are settled in a row and those are enough long to get a full slice image of a specimen. 1984 X-ray detectors are set in array to measure transmission X-ray.

The specimen is set between X-ray source tube and detectors and it rotate 360 degree for collecting data. This method enables shortening time and has high reliability on mechanical movement. One slice data was taken by one turning of specimen.

(1) X-ray generator unit

X-ray unit consists of high voltage generator unit and x-ray source tube and are connected with high voltage cable. The supplied high voltage is controlled with the microprocessor controller. X-ray source tube is fixed on base of system. 450kV type X-ray source tube which is enough high power to penetrate test specimens was adopted.

(2) X-ray detector unit

X-ray detector unit is possible to change the distance from X-ray source tube which settled on rail and the distance is decided by required magnifications. A collimator is settled in front of the scintillator to be narrow transmission X-ray for shielding radiation and ensuring resolution of graphics. The collimator is made from tungsten alloy and it is possible to adjust the width of slit. The detector that has high scrubbing efficiency and the sensibility for X rays is required to detect transmission X-ray. Hence the tungstic acid cadmium ($CdWO_4$) is adopted for our detector. $CdWO_4$ type detector is superior to gadolinium oxide sulphur (GOS) type detector in resolution.

(3) Specimen movement unit

Specimen movement unit has a rotatable specimen table which can move to the vertical direction. And it has a specimen support tube which can adjust a specimen on the rotatable specimen table. Specimens are inserted by remote operation into the specimen support tube which is mounted on the rotatable specimen table. The direction of movement under scanning is below. The specimen support tube is used by manipulators with considering safety and certainty.

(4) Control board and data analyze unit

The control board unites and controls a power-supply unit, an electric distribution unit, a safety circuit, and a control circuit of the system. The main body of the system is large, and hence it is settled in first basement except emergency stop switch.

The data processing unit consists of a host computer for data collection from detectors and a computer which perform three dimensions processing of collected data. And this computer controls the movement of the X-ray detector unit and the rotatable specimen table.

4. Inspection objects

We assume inspection object as stainless tubes of irradiation capsules (Maximum diameter: 110mm, Width: 3.5mm, length: 1,000mm, Weight: 30kg), and fuel rods with uranium pellets (Maximum diameter: 12.5mm, length: 1,000mm, Weight: 1kg).

Various types of specimens such as CT type specimen are set inside irradiation capsules and required distance to penetrate is about 45mm.

About uranium pellets, we assume irradiated pellets (uranium dioxide, 10.2 g/cm^3 in density) with thermo couple inserted in drilled center hole.

5. Measurements

5.1 Performance tests using imitation specimen.

(1) Imitation pellet for performance tests

Figure 4 shows a cross sectional drawing of a fuel rod which used for high burn up fuel irradiation tests. An imitated pellet is made from chromium-molybdenum steel (10.18 g/cm^3) in consideration of the density of uranium dioxide. It has center hole with inserted thermo couple and slits as simulated crack. Figure 5 shows the imitated pellet and a measured 3D graphic.

(2) Resolution performance tests

The resolution tests are performed to confirm resolution performance of tomography using platinum double wire which is used as center line of thermo couple (Diameter: 0.3mm) which used in fuel rods for ramping tests. X-ray CT measurements are performed to platinum double wire specimens (Diameter: 0.8～0.05mm, Distance of wires: 0.8～0.05mm) and it is confirmed to recognize up to 0.16mm. Figure 6 shows the results.

5.2 Performance tests using an irradiated fuel rod

(1) Irradiation history of the test specimen.

Performance tests of this X-ray system were performed using an irradiated fuel rod. The fuel rod was used in commercial reactor and then it was shorten and used for ramping test with instrumentation in JMTR. The burn up of the fuel rod is 25GWd/t and output of that ramping test is 400W/cm.

(2) Results of tomography

Figure 7 shows a transmission X-ray graphics of the fuel rod. Whole fuel rod was scanned by 0.1mm pitch slices. And then a position where thermocouple was inserted was scanned in detail. The internal components such as double instrumentations were clearly observed in transmission X-ray graphics.

The inserted thermocouple condition, surface cracks of the pellet caused by instrumentation were observed by this graphics made from 0.1mm pitch slice measurement.

6. Conclusion

The three dimensional X-ray Computerized Tomography (CT) inspection system for nondestructive inspection has been utilized. And performance tests were performed for this system. The results of tests are as follows,

(1) Maximum size of specimen for this system is the size of large type capsule of JMTR (Diameter: 100mm, Weight: 30kg).
(2) Observations of internal condition of a fuel rod (Consist of UO2 pellets, Pellet diameter: 10mm) are performed and high resolution cross sectional graphics are

obtained from a fuel rod.

(3) It was confirmed to be able to perform remote operations of irradiated specimens without any problem.

(4) It is planned to compare tomography and metallography graphics of pellets.

By this development of the X-ray CT inspection system, it became possible to provide data with high technical value for post irradiation examination of high burn-up fuels and large type specimens.

Referrences

1) YXLON International X-Ray GmbH "Three dimension CT application to car parts such as aluminum casting goods."

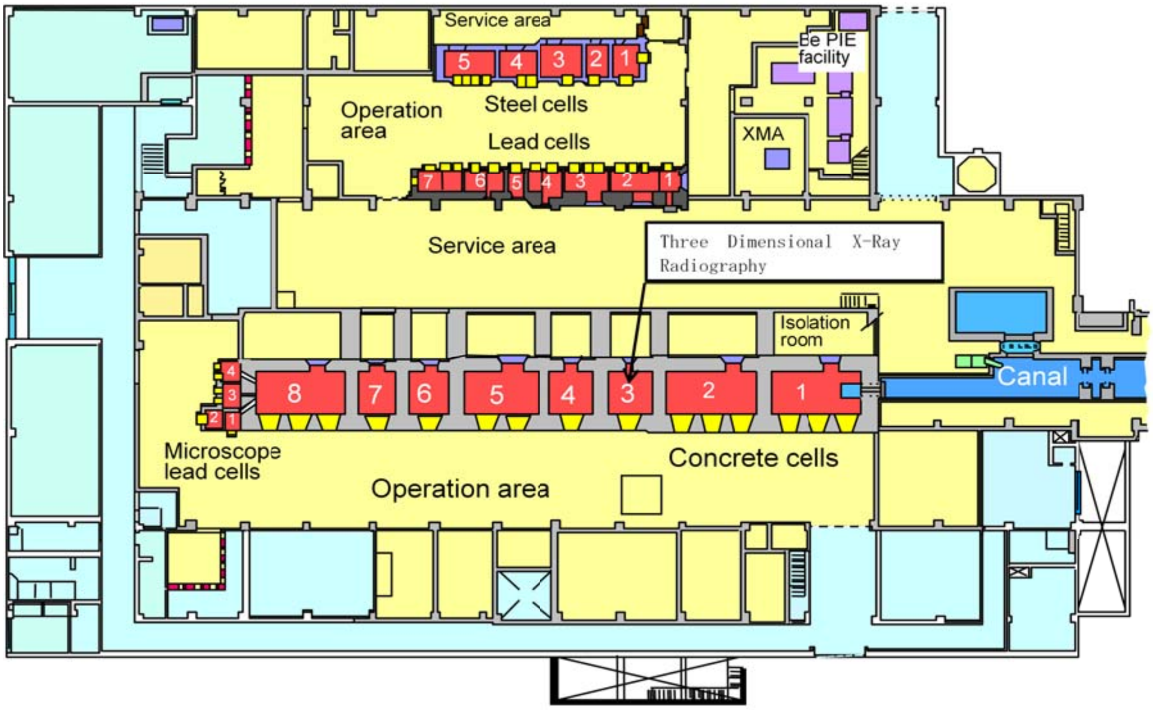

Figure 1　Arrangement of the hot laboratory

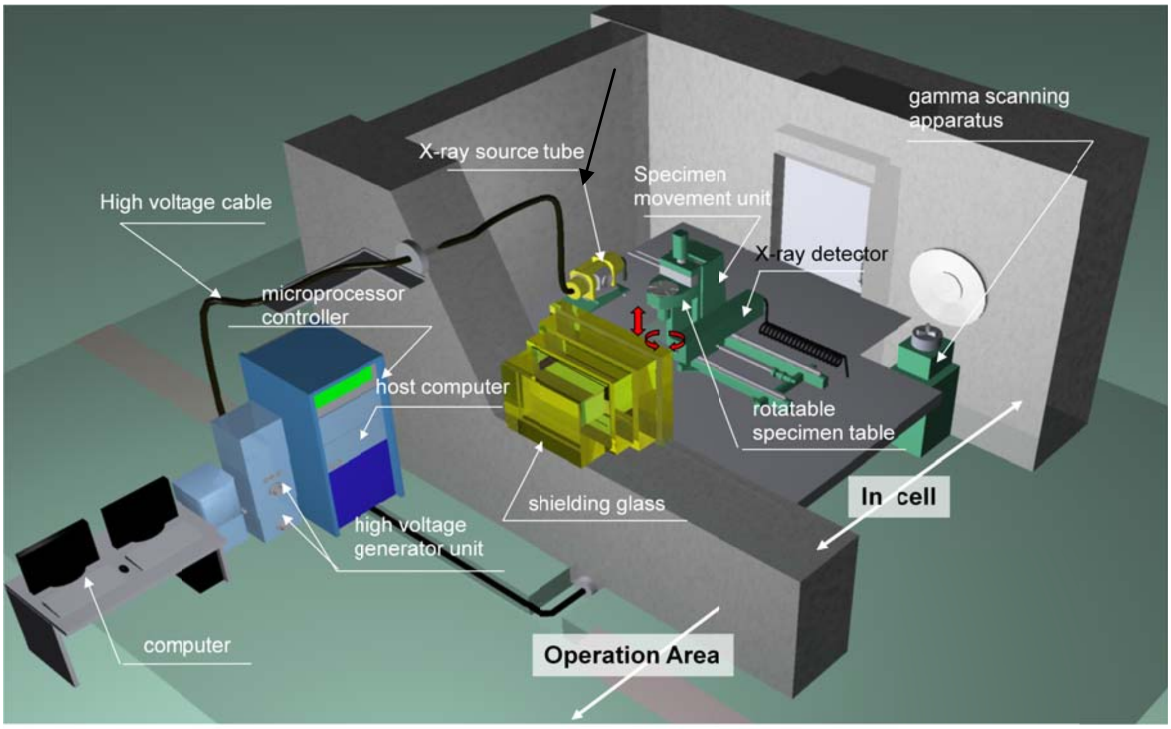

Figure 2　Schematic drawing of the X-ray CT inspection system

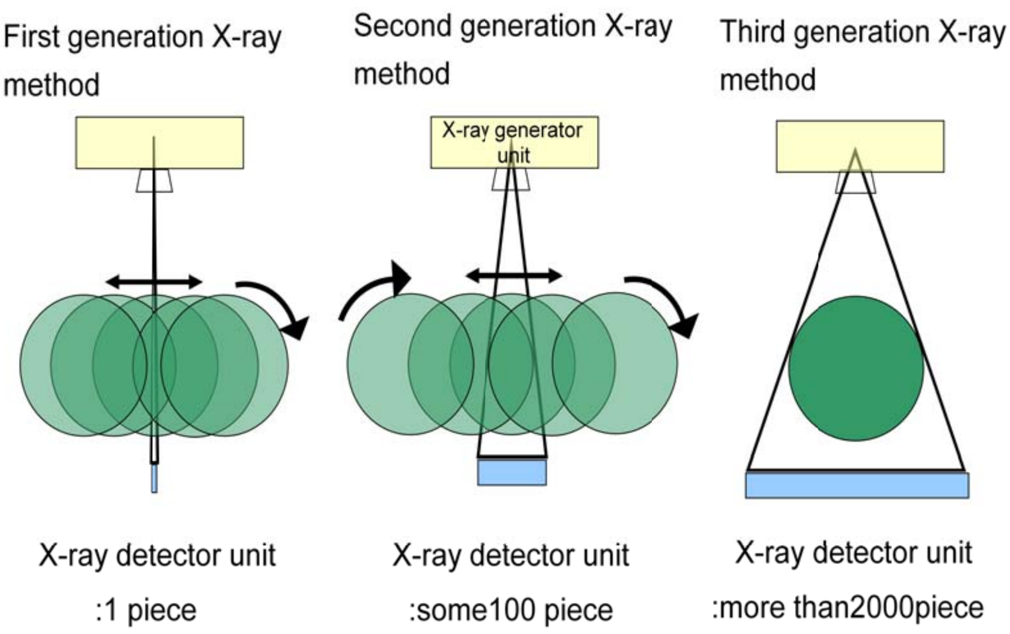

Figure 3　Various scanning methods

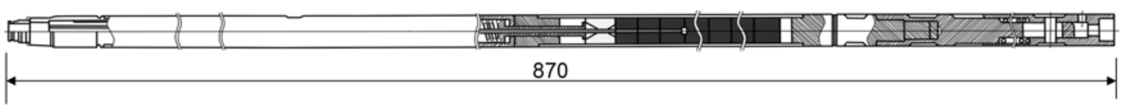

Figure 4　Cross sectional drawing of a fuel rod

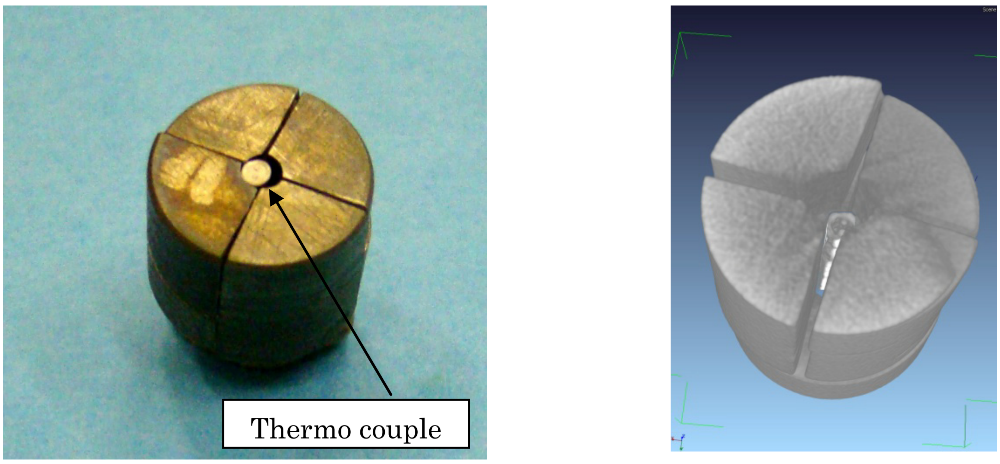

Figure 5　The imitated pellet and a measured 3D graphic

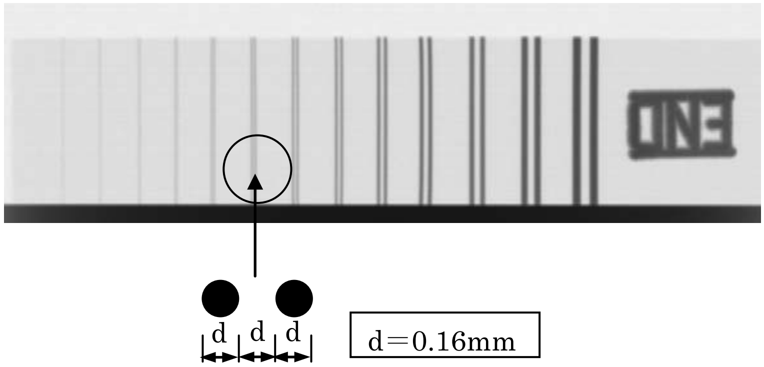

Figure 6　Resolution performance test

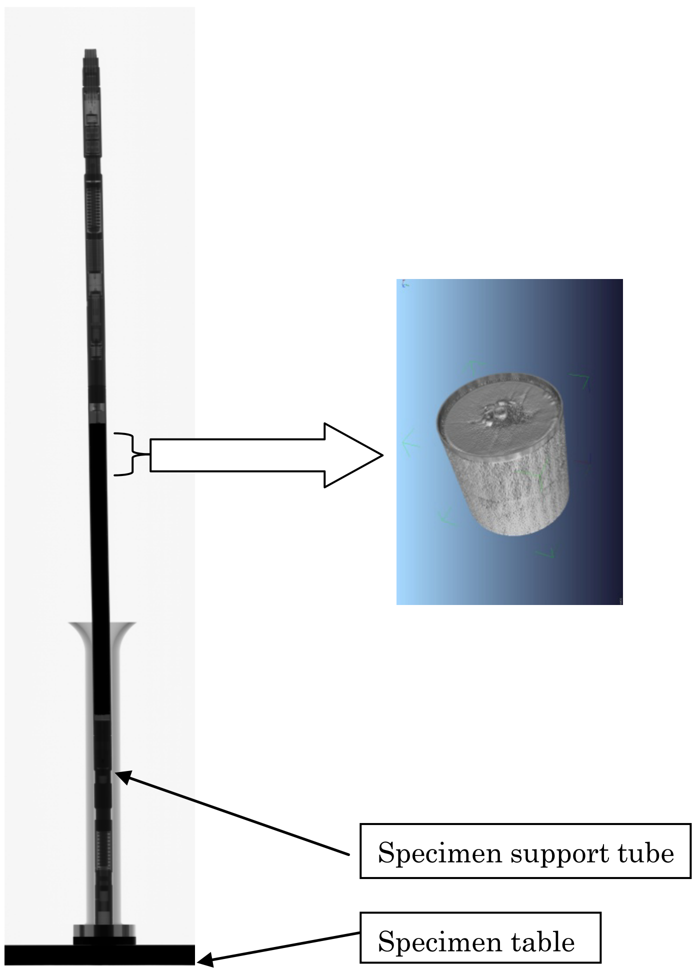

Figure 7　Transmission X-ray graphics of a fuel rod

Table 1 Major specification of X-ray CT inspection system

	Specifications
CT scanning method	Third generation X-ray method
X-ray generator unit	Tube voltage : 20~450 kV Tube current : 0~15mA
X-ray detector unit	Detector length : 504mm Number of pixels : 1,984 piece Collimator slit : 0,1～3mm Adjustable Collimator thickness : 40mm (Tungsten)
Specimen movement unit	Max. Vertical distance : 1,000mm Min. distance : 0.1mm Min. angle of rotation : 0.025°
Size of inspection objects	Capsules Max. diameter : 110mm Max. weight : 30kg Fuel rods Max. diameter : 12.5 mm Length : 1,000mm Weight : 1kg

Appendix Presentation materials at 3rd International Symposium on Material Reactor

The 3rd International Symposium on Material Test Reactor was held June 21-23, 2010 at the Nuclear research Institute Rez plc. and Research centre Rez Ltd., Czech Republic. The objective of the meeting was to provide and opportunity for technical and operational information exchange among international test reactor facilities.

The presentation materials related in "Nondestructive Testing by Three-dimensional X-ray Radiography" are attached as an appendix.

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Introduction

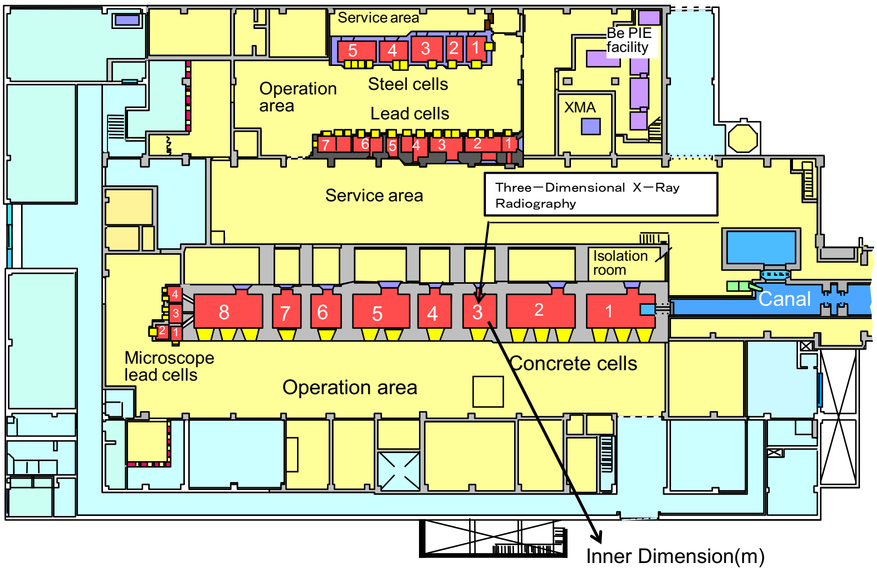
The JMTR-HL plans to put a three dimensional X-ray radiography system in place until the restart of JMTR in order to satisfy the requirement of valuable irradiation data for safety and plant life time management of nuclear power plants in the future.

Three dimensional X-ray radiography method
CT(Computed Tomography)

↓

Provide data with high technical value

Arrangement of the Hot Laboratory



Inner Dimension(m)
3(w)x3(D)x5.5(H)x1.0(shielding wall)

2

Inspection objects

1. Large stainless capsules

   Maximum diameter :110mm

   Thickness : 3.5mm

   Length:1,000mm

   Weight:30kg

2. Irradiated fuel rods(High burn up fuels)

   Maximum diameter :12.5mm

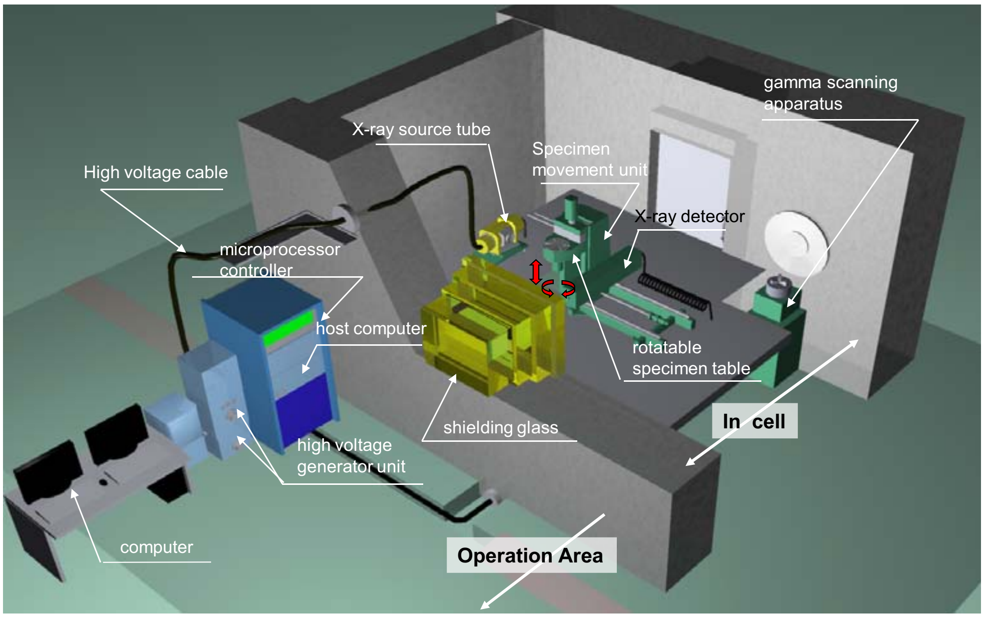
   Length:1,000mm

   Weight:1kg

   UO_2 Pellets(:10.2g/cm^3 in density)

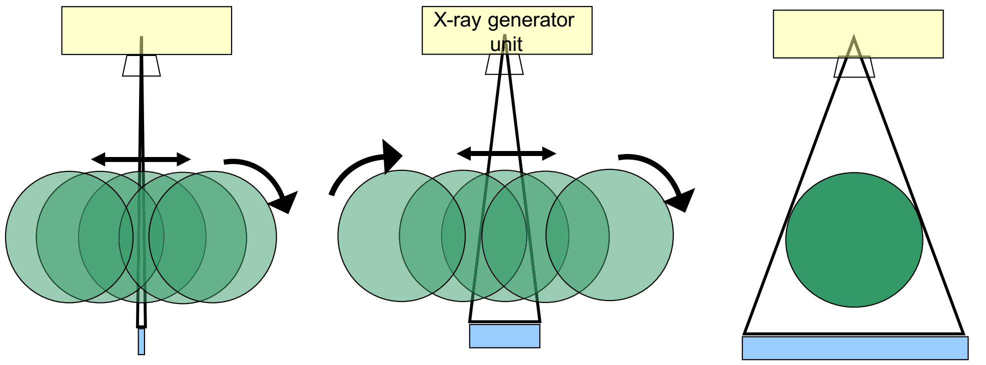
3

Schematic drawing of the X-ray CT inspection system



Various scanning methods

First generation X-ray method	Second generation X-ray method	Third generation X-ray method



X-ray detector unit :1 piece	X-ray detector unit :some100 piece	X-ray detector unit :more than2000piece

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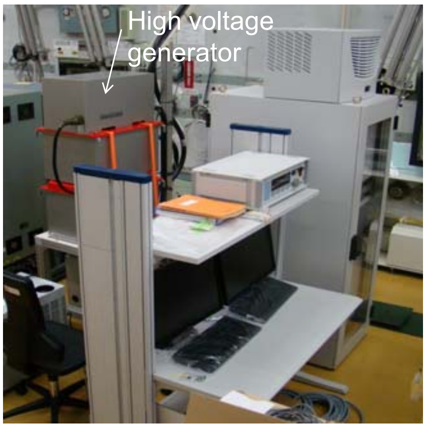
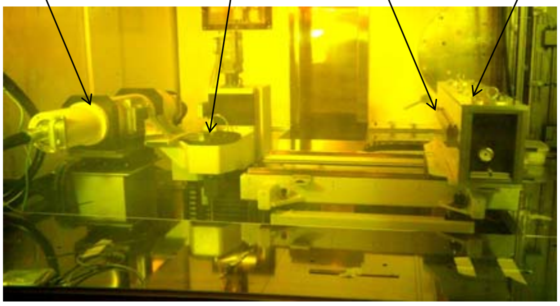
Photograph in investigation Operation and Hot cell



Operation area



In Hot cell

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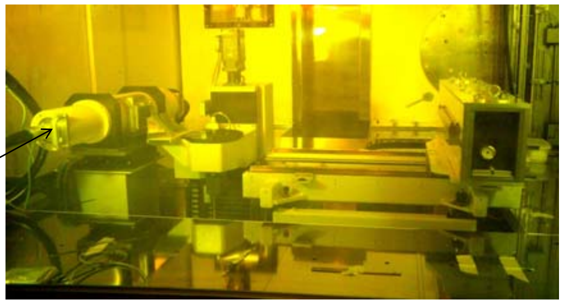
Details of device

1．X-ray generator unit

Tube voltage : 20～450kV
Tube current ： 0～15mA



X-ray generator unit consists of high voltage generator unit and x-ray source tube.

The supplied high voltage is controlled with the microprocessor controller.

450kV type X-ray source tube which is enough high power to penetrate test specimens was adopted.

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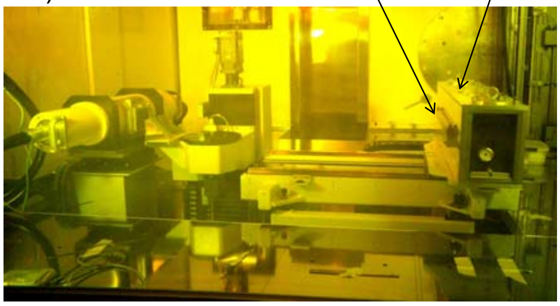
Details of device

2. X-ray detector unit(Line Detector Array)
   Scintillator Material : $CdWO_4$ (tungstic acid cadmium)
   Collimator slit 0.1mm～3mm (Adjudtable)
   Collimator thickness: 40mm(tungsten)
   Number of channels
      Pixel size: 0.254mm
      number of pixels: 1,984 piece
      detector length: 504mm



X-ray detector unit is possible to change the distance from X-ray source tube.

A collimator is settled in front of the scintillator to be narrow transmission X-ray for shielding radiation and ensuring resolution of graphics.

The detector that has high scrubbing efficiency and the sensibility for X rays is required to detect transmission X-ray. → the tungstic acid cadmium is adopted.

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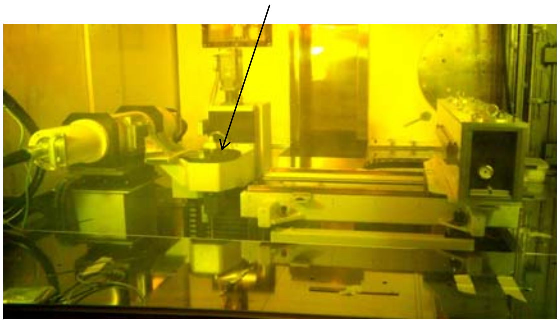
Details of device

3. Specimen movement unit
   Max. Vertical distance: 1,000mm
   Min. distance: Amount of 0.1mm
   Min. angle of rotation: 0.025 degrees



Specimen movement unit has a rotatable specimen table which can move to the vertical direction.

Specimens are inserted by remote operation into the specimen support tube which is mounted on the rotatable specimen table.

The specimen support tube is used by manipulators with considering safety and certainty.

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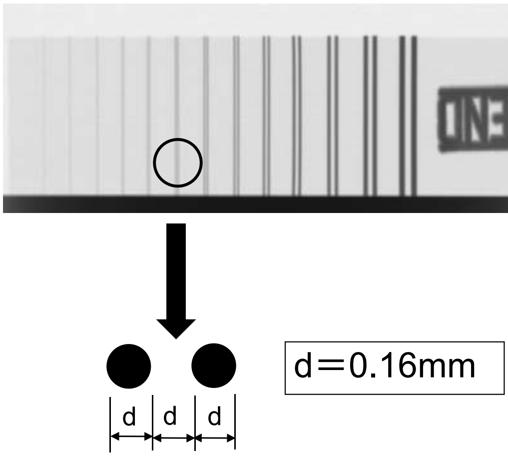
Resolution Performance tests



The resolution tests using platinum double wire were performed.

X-ray CT measurements are performed to platinum double wire specimens (Diameter: 0.8～0.05mm, Distance of wires: 0.8～0.05mm) and it is confirmed to recognize up to 0.16mm.

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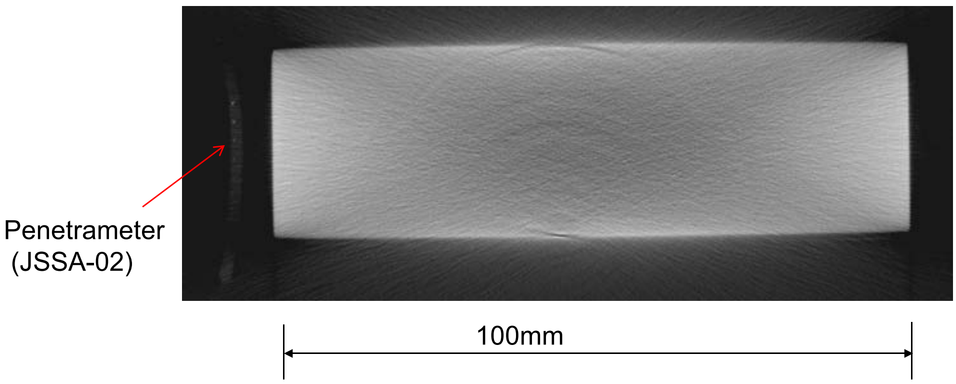
Performance tests using a large size SUS



1.Requirements for the large size stainless steel capsules

- The penetration ability requires more than 40mm in the iron- equivalent thickness.
- It was confirmed to penetrate even by stainless steels of 100mm in thickness.

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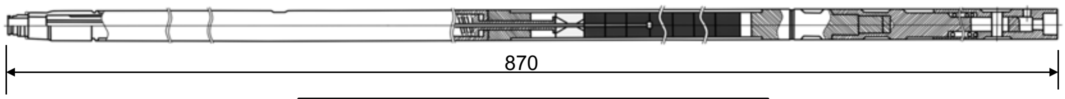
Performance tests using an irradiated fuel rod(1/2)



Burn up : 25GWd/t
Linear heat rate :400W/cm

Performance tests of this X-ray system were performed using an irradiated fuel rod.
The fuel rod was used in commercial reactor and then it was shorten and used for ramping test with instrumentation in JMTR.
The burn up of the fuel rod is 25GWd/t and output of that ramping test is 400W/cm.history of the test specimen.

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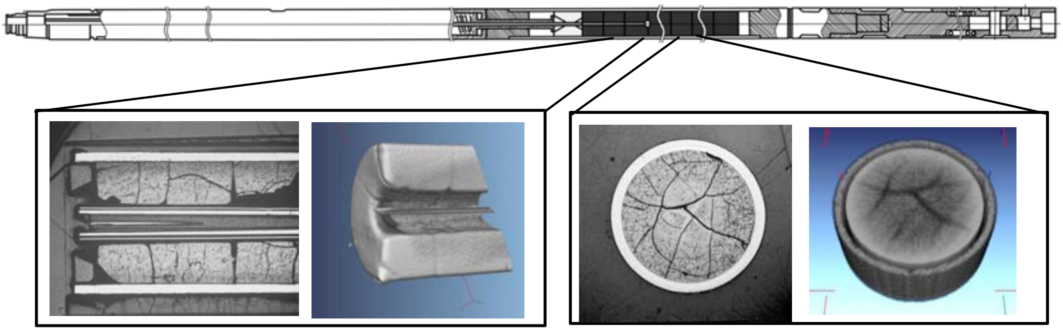
Performance tests using an irradiated fuel rod(2/2)



Metallography (Longitudinal section) | tomography | Metallography (cross-section) | tomography

2.Requirements for the irradiated fuel rods(high burn-up fuels)
- Influence of gamma ray emitted from the radiation source of the subject inside.
- It was confirmed to obtain a clearer image by applying the offset method to taking a picture, and suppressing the influence of the γ-ray.

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Result

The three dimensional X-ray Computerized Tomography (CT) inspection system for nondestructive inspection has been utilized. And performance tests were performed for this system. The results of tests are as follows,

(1)Maximum size of specimen for this system is the size of large type capsule of JMTR (Diameter: 110mm, Weight: 30kg).

(2)Observations of internal condition of a fuel rod (Consist of UO^2 pellets, Pellet diameter: 10mm) are performed and high resolution cross sectional graphics are obtained from a fuel rod.

(3)It was confirmed to be able to perform remote operations of irradiated specimens without any problem.

It became possible to perform X-ray CT tests of high burn up fuels which will be required after restart of JMTR.

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Conclusion

This system can be applied to one of new non-destructive inspections which obtains information about the structure of irradiated fuel rod and the irradiation capsule, as follows;

(1) Fuel rod : the grasp of change in fuel pellet internal state according to its burn-up, and the confirmation of integrity of instrumentation equipment in fuel rod.

(2) Capsule : the inspection of arrangement in space of irradiation sample of materials and construction elements.

It is expected that promotion of efficiency and the rationalization of the post irradiation examination progress by this system.

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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	$1\ \mu=1\mu m=10^{-6}m$

（第8版，2006年改訂）