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Annual Report of the Neutron Irradiation and Testing Reactor Center FY 2008

(April 1, 2008 – March 31, 2009)

Neutron Irradiation and Testing Reactor Center

Oarai Research and Development Center

December 2009

Japan Atomic Energy Agency

日本原子力研究開発機構

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Oarai Research and Development Center
Japan Atomic Energy Agency
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The JMTR, one of the most high flux test reactors in the world, has been used for the irradiation experiments of fuels and materials related to LWRs, fundamental research and radioisotope productions. The JMTR was stopped at the beginning of August 2006 to conduct refurbishment works, and the reoperation will be planned from FY 2011. After reoperation, the JMTR will contribute to many fields, such as the lifetime extension of LWRs, expansion of industrial use, progress of science and technology.

This report summarizes the activities on refurbishment works, development of new irradiation techniques, enhancement of reactor availability, etc. in FY 2008.

Keywords : JMTR, Annual Report, Refurbishment, Restart, Utilization Promotion, Irradiation Technology

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照射試験炉センターの活動報告（２００８年度）
(2008年4月1日～2009年3月31日)

日本原子力研究開発機構大洗研究開発センター
照射試験炉センター

（2009年 9月 28日受理）

世界有数の高中性子束を有する材料試験炉JMTR（熱出力50MW）は、軽水炉燃料・材料の照射試験や基礎研究、ラジオアイソトープ（RI）の製造等に利用されてきた。平成 19 年度から改修を開始し、平成23年度から再稼働する計画である。再稼働後は、軽水炉の長期化対策、産業利用の拡大、科学技術の向上のために利用される予定である。

本報告は、JMTRの改修工事の進捗、照射試験に係る新技術の開発、原子炉稼働率の向上等について、平成20年度の活動をまとめたものである。

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1. Introduction

The Japan Materials Testing Reactor (JMTR), which is a light water moderated tank-type reactor with thermal power of 50 MW, is one of the world's highest neutron flux reactors within currently operating test reactors.

Main specifications of the JMTR are summarized in Fig.1.1.1 with bird's-eye view of the reactor. Since achieving the first criticality in March 1968, the JMTR has been used to obtain the valuable irradiation data on the durability and integrity of reactor fuels and materials, basic nuclear research and to produce many kinds of radioisotopes (RIs). Operation of the JMTR was, however, halted in August 2006 after its 165^{th} cycle operation.

The restart of the JMTR has been strongly requested from various users as the only irradiation testing reactor in Japan. Moreover, the Atomic Energy Commission, Nuclear Safety Commission of Japan, the Council for Science and Technology Policy, and other committees evaluated that the JMTR should resume operation as soon as possible to meet a wide variety of irradiation needs. Considering these requests, the Japan Atomic Energy Agency (JAEA) made an official decision to restart the JMTR, and then started the refurbishment works from FY 2007.

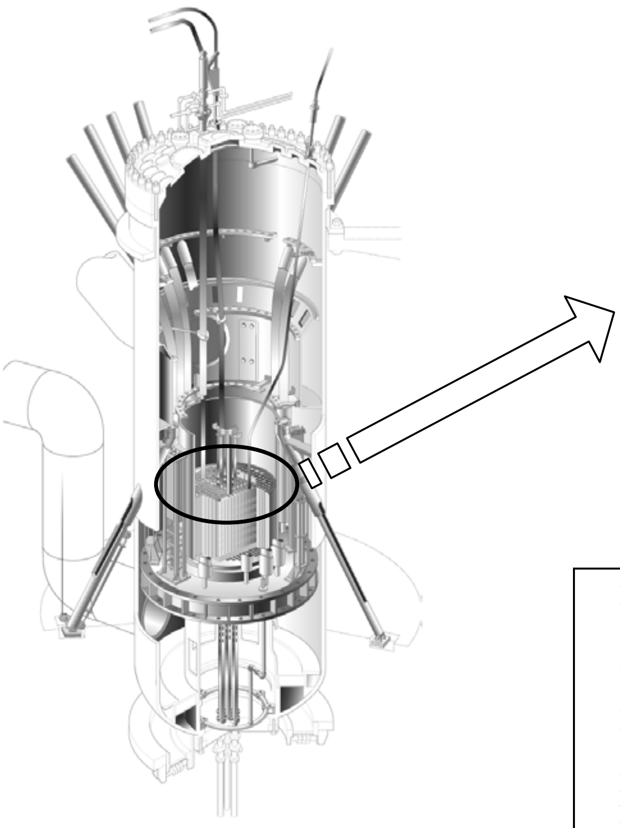
The new JMTR is expected to contribute many fields: the lifetime extension of LWRs (aging management of LWRs, development of next generation LWRs, etc.), expansion of industry use (production of the medical radioisotope ^{99m}Tc, etc.), progress of science and technology (namely, basic research on nuclear energy) and so on. To propose attractive irradiation test data to users, advanced technologies with new irradiation techniques are being developed.

Furthermore, a user friendly management of the JMTR will be achieved by improvements of reactor operation rate, shortening the time to get irradiation results, etc. In addition, an international contribution, namely not only for domestic users but also foreign users, is under consideration. Aiming at the internationally utilized facilities as an Asian center of materials testing reactor, establishment of international networks among materials testing reactors in the world is also under discussion now.

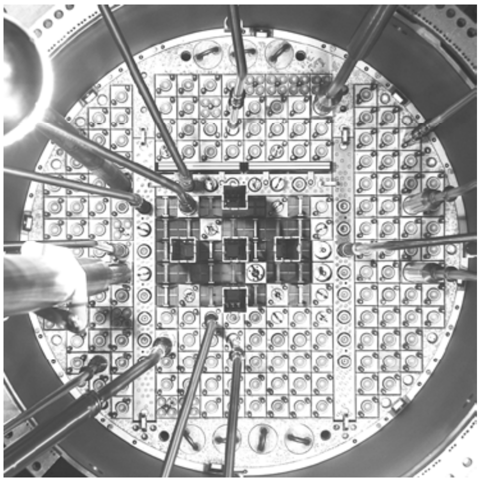
In FY 2008, application for regulatory approval of reactor facilities to be refurbished was completed, and renewal of the feed and exhaust air system for ventilation in the controlled area (the reactor building), UCL (Utilities cooling loop) system to supply coolant with irradiation facility, etc. was finished. The refurbishment work is on going as scheduled, and restart will be from FY 2011. Moreover, corresponding to new utilization requests, new irradiation facilities which are to be installed by users funds are being discussed.

In addition, an investigation to improve the calculation accuracy of fast/thermal neutron fluencies is starting to show irradiation data with high technical value. Development of irradiation facilities for an aging management of LWRs is proceeding, and feasibility study for producing ^{99}Mo, that is the parent nuclide of the medical radioisotope ^{99m}Tc,is conducting.

To improve usability, feasibility study to achieve the high reactor-operation-rate of JMTR is also carrying out aiming at the achievement of world-highest level of 70% reactor-operation-rate; the reactor-operation-rate was about 50% before the refurbishment. From the feasibility study, it is found that about 210 days operation per year (the reactor-operation-rate is about 60%) will be possible, although that for before refurbishment was about 180 days per year.



Reactor pressure vessel



Reactor core

Reactor type	**: Tank type**
Thermal power	**: 50MW**
Fuel type	**: ETR type (19.7%^{235}U enrichment)**
Moderator	**: Light water**
Coolant	**: Light water**
Reflector	**: Beryllium**
Neutron flux	**: 4.0×10^{18} $m^{-2}s^{-1}$(Fast)**
	: 4.0×10^{18} $m^{-2}s^{-1}$(Thermal)

Fig.1.1.1 Outline of JMTR.

2. Refurbishment of JMTR

2.1 Renewal of Reactor Facilities

Various facilities are to be renewed steadily during four-years in refurbishment period, and the new JMTR is to be restarted form FY 2011. During the refurbishment period, maintenance activities to keep a safety performance must be also carried out in parallel with the refurbishment works. Therefore, refurbishment work should be carried out with efficiently scheduled plan; utility facilities such as power supply system, boiler component, feed and exhaust air system are to be renewed in the refurbishment period, and then, the facilities in the reactor building such as reactor control system, control rod drive mechanism, reactor cooling system are to be renewed. Reactor facilities to be renewed are illustrated in Fig.2.1.1, and the refurbishment schedule is shown in Fig.2.1.2.

In FY 2008, the renewal work of power supply system, boiler, radioactive waste facility, reactor cooling system, etc. was carried out as scheduled (Appendix 1). From FY 2009, reactor control system, process control system, nuclear instrumentation system and the control rod drive mechanism in the instrument-and-control system, motors of primary pumps, transfer pumps, charging pumps, etc. in the primary cooling system, circulating pumps, auxiliary pumps, etc. in the secondary system, drainage system in the radioactive waste facility, etc. are to be renewed.

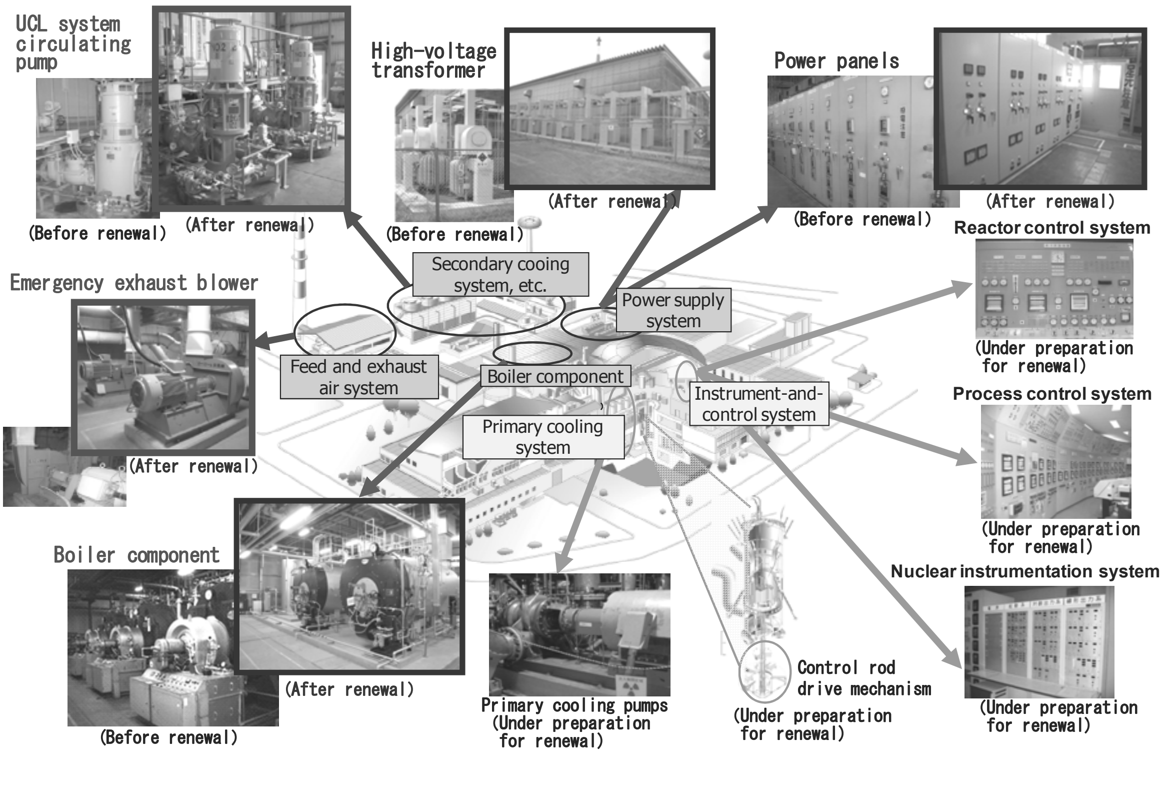


Fig.2.1.1 Refurbishment of reactor facilities.

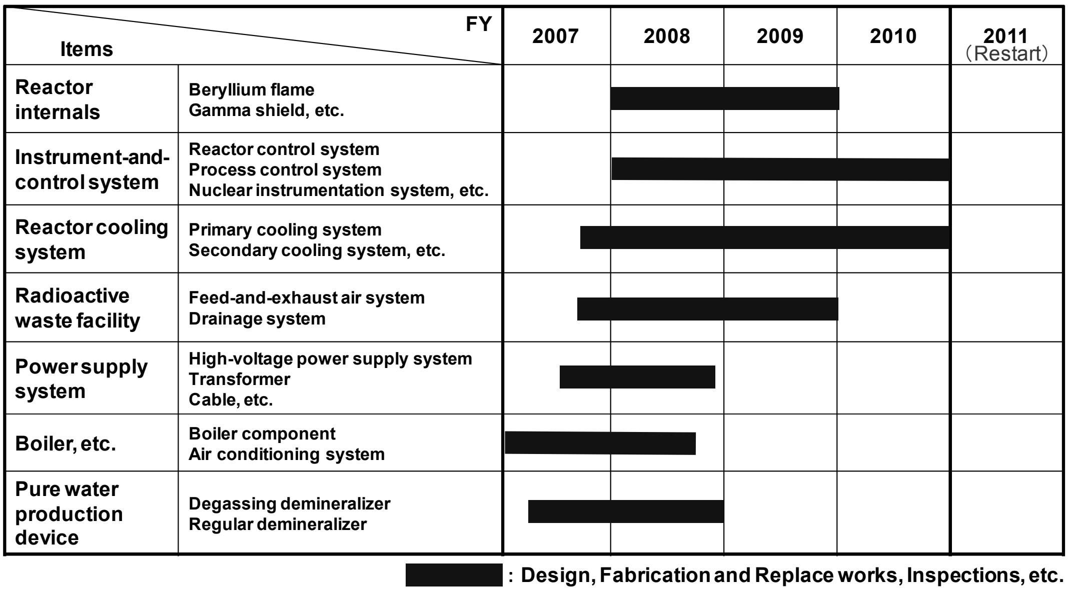


Fig.2.1.2 Refurbishment work schedule.

2.2 Preparation of Irradiation Facilities

Corresponding to the new requests for utilization of the JMTR, new irradiation facilities, i.e. irradiation test facilities of materials and fuels, production facilities for ^{99}Mo that is the parent nuclide of the medical radioisotope ^{99m}Tc, will be planned to be installed in JMTR. The preparation schedule is summarized in Fig.2.2.1. New irradiation facilities are to be installed by users funds, and the facilities of (1) and (2) in Fig.2.2.1 are under installation.

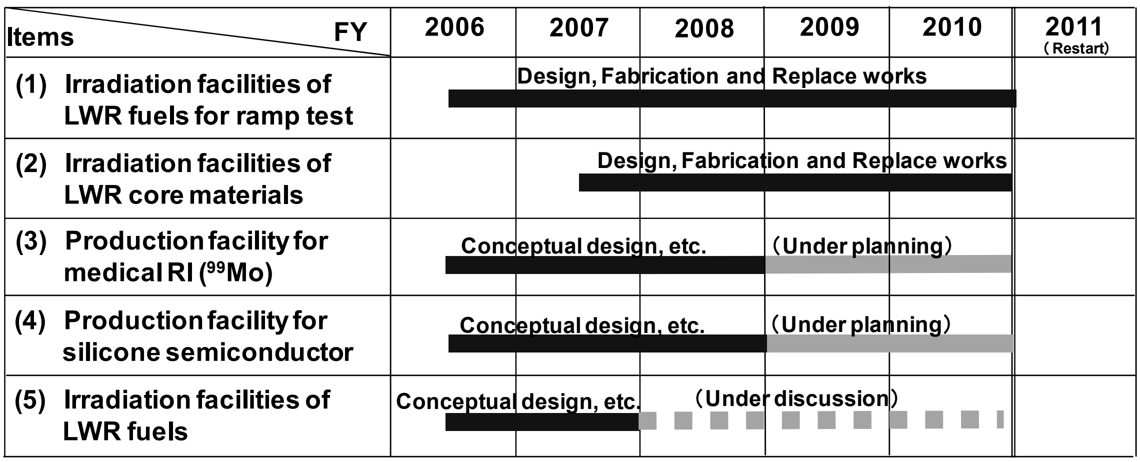


Fig.2.2.1 Preparation schedule for irradiation facilities.

3. Utilization Promotion of JMTR

In this fiscal year, the 2nd and 3rd JMTR Steering Committee were held on Oct. 17, 2008 and Mar. 10, 2009 respectively. The meeting was established for the administration of JMTR from viewpoints of the reflection of requests from JMTR users in February 2008.

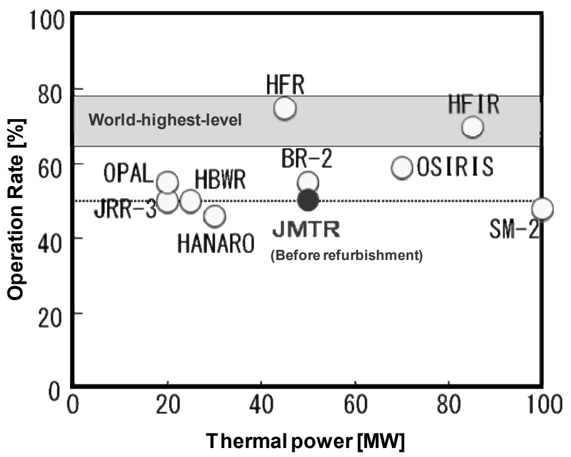
In these meetings, several ideas and/or comments on the usability improvement of JMTR such as reactor operation rate, turnaround time which is the time from application to getting data and irradiation fee were proposed from committee members.

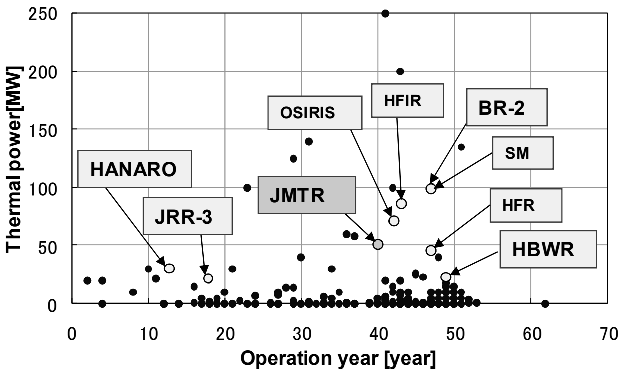
3.1 Improvement of Reactor-operation-rate

The maximum reactor-operation-rate of JMTR was about 50% (180 operating days per year) before the refurbishment. However, corresponding to the usability improvement and the increase in irradiation requests, the reactor-operation-rate at world top class (~70%, see Fig.3.1.1) should be realized after the refurbishment. As the first step, the feasibility study was carried out to realize 210 operating days per year, which is equivalent to about 60% of reactor-operation-rate.

Figure 3.1.2 shows the JMTR operation plan after refurbishment. It is possible to increase in the reactor-operation-rate with decreasing the reactor shutdown period by optimizing the maintenance works as well as by reducing the period of periodical inspection with introducing effective work-shift.

From a result, 210 operating days per year would be possible to realize for the JMTR.





Source：IAEA Research Reactor Database Web Site (28/8/2007) (http://www.iaea.or.at/worldatom/rrdb/)

Fig.3.1.1 Operational status of research reactors in the world.

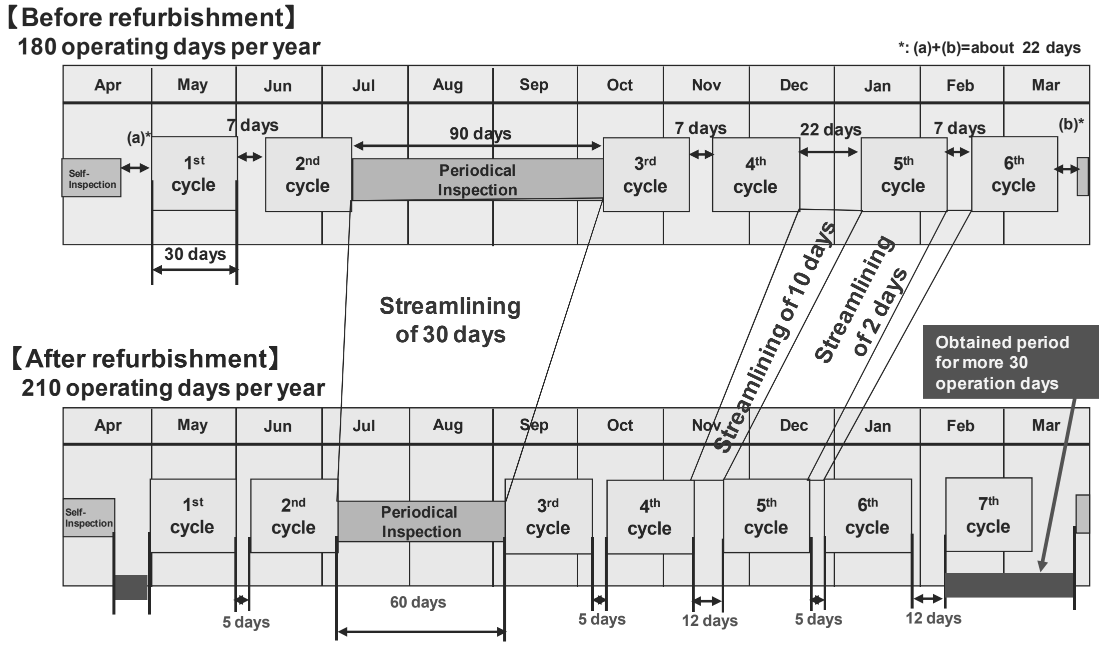


Fig.3.1.2 JMTR operational plan after refurbishment.

3.2 Shortening Turnaround Time

The irradiation utilization of the JMTR is the following procedures:

1) Submission of utilization application from users to the JMTR section.
2) Design and manufacture of irradiation capsule.
3) Irradiation test and post-irradiation examinations(PIEs).
4) Acquisition of irradiation data.

The reduction of the turnaround time for above procedure has been investigated.

Capsules for irradiation tests have two types, the one is the instrumentation capsule where the in-situ instrumentation is possible, and the other is non-instrumentation capsule without in-situ measurements. From results of the investigation, it is concluded that the period of designing and manufacturing of capsule could be shortened maximum about 6 months by introducing the standardization capsule.

3.3 Achievement of Attractive Irradiation Expenses

In the re-operation of JMTR, it is important to realize more attractive irradiation fee in comparison with other testing reactors in the world. Therefore, the irradiation fee has been discussed from a viewpoints of decreasing in the JMTR operational cost. Prior to that, an investigation has been made on the irradiation utilization for some research and testing reactors such as Holland, Belgium, Korea and so on. From the investigation, it can be said that production of radioisotopes (RI) as an irradiation utilization of the JMTR will be increasing slightly. On the other hand, it was found that there's a strong request for domestic production of some RIs such as ^{99}Mo (which is the parent nuclide of ^{99m}Tc (a RI used for medical diagnosis) and the 100% of which is now imported from overseas). Thus, the discussion concerning the establishment of utilization fee for RI production has been started in reply to the user's demand.

3.4 Domestic Production of ^{99}Mo

^{99m}Tc ($T_{1/2}$: 6 hours), the daughter nuclide of ^{99}Mo ($T_{1/2}$: 66 hours), is the important radioisotope for the diagnostic imaging of the diseases including cancer. In Japan, the 100% of ^{99}Mo, the medicine raw materials of ^{99m}Tc, is imported from foreign countries.

The five testing rectors (NRU, BR-2, OSIRIS, HFR and SAFARI-1) are used for production of ^{99}Mo by fission method((n,f) method) with high enriched ^{235}U. However, the shortage crisis of the ^{99}Mo production due to aging problem of these reactors is a currently serious issue in the world. Especially, the production license of ^{99}Mo in NRU of AECL (Atomic Energy Canada Limited), which produce ^{99}Mo about 43% in the world, is effective up to 2011, and it is uncertain whether the license is updated or not.

Under the crisis situation, the NEA Workshop on "the Security of Supply of Medical Radioisotopes" (29th-30th January, 2009) was held by the request of a Canadian government, and the problem of ^{99}Mo stable supply in future was discussed.

Especially from a viewpoint of the stable supply and the international responsibility, domestic production of ^{99}Mo is important for our country; Japan uses about 14% of the total production in the world.

From the viewpoint of the above-mentioned situation, "Special Committee for Domestic Production of ^{99}Mo" was established under the JMTR Steering Committee, and feasibility study and technical discussion for the domestic production was started with an industrial collaboration.

In the committee, discussions were focused on the ^{99}Mo production by the neutron activation method ((n, γ) method), which is thought to be more useful rather than the (n,f) method.

In the discussion of the irradiation target, it is clear that MoO_3 pellet(95% theoretical density) is possible to produce from a trial examination result. Moreover, it is also clear that the ^{99}Mo production at amount of 1000Ci per week is possible by the Hydraulic Rabbit irradiation facility in JMTR (see Fig.3.4.1). Examination of the ^{99}Mo absorbent will be planned in future.

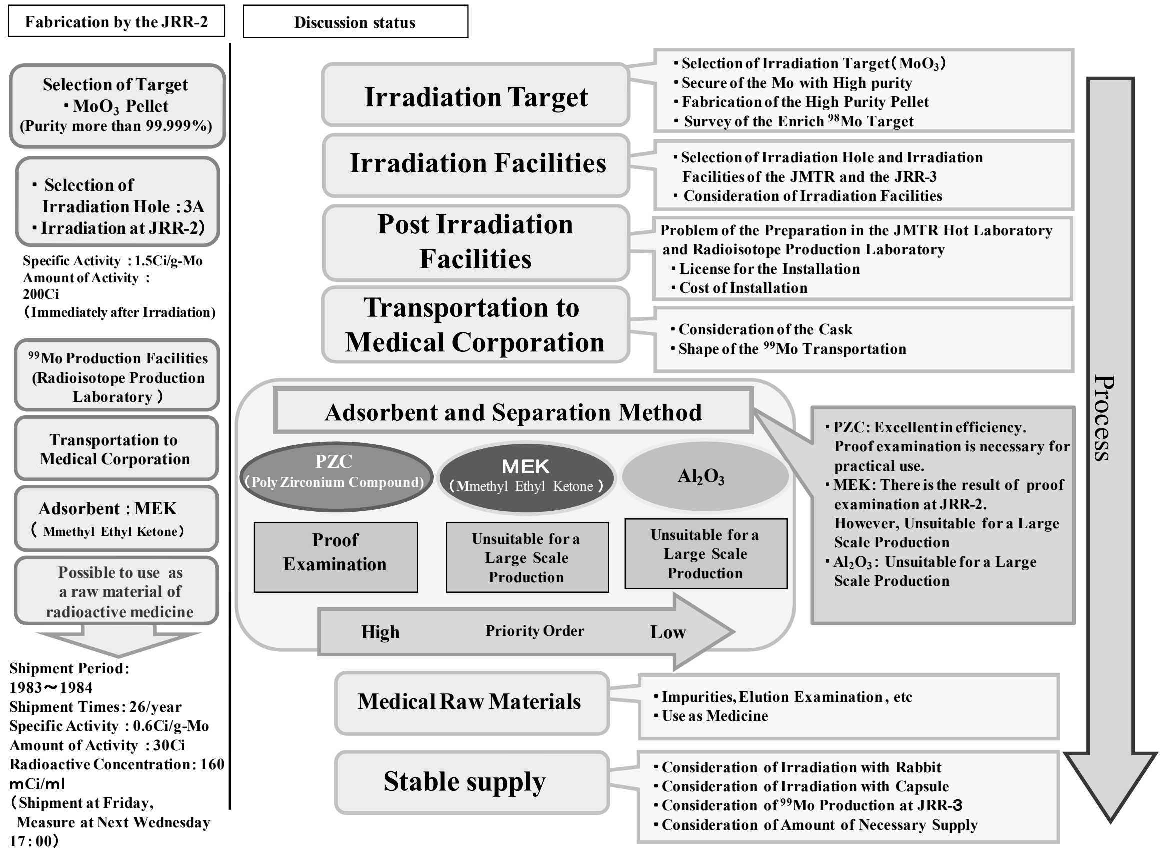


Fig.3.4.1 Technical discussion for (n, γ) method in the "Special Committee for Domestic Production of ^{99}Mo".

4. Development of Irradiation Technology

4.1 Preparation of New Irradiation Engineering Building

To develop the irradiation capsules, construction of new irradiation engineering building was completed in August, 2008. High-performance SEM, vacuum electric furnaces, electronic balances, etc. were installed in the new building, and capsule developments were started.

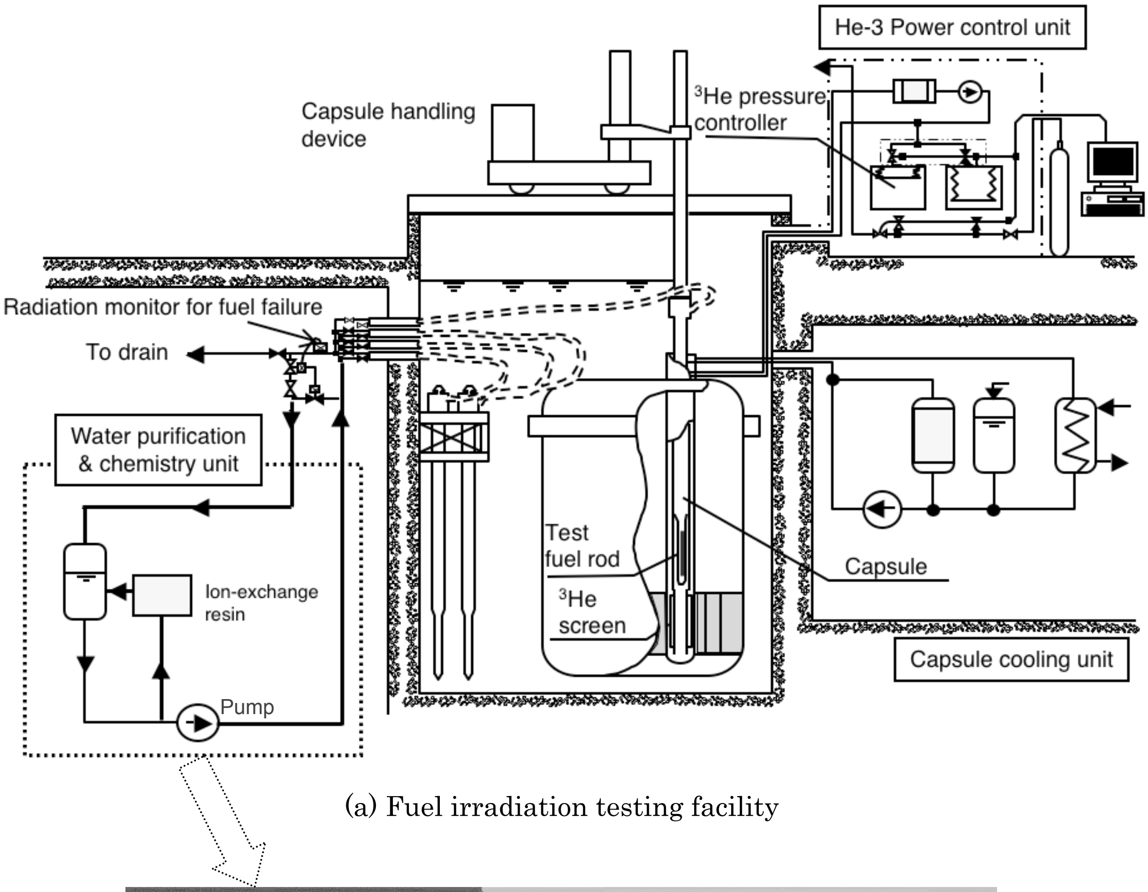
4.2 Irradiation Technology for LWR Fuel and Material

4.2.1 Development of Fuel Irradiation Testing Facility

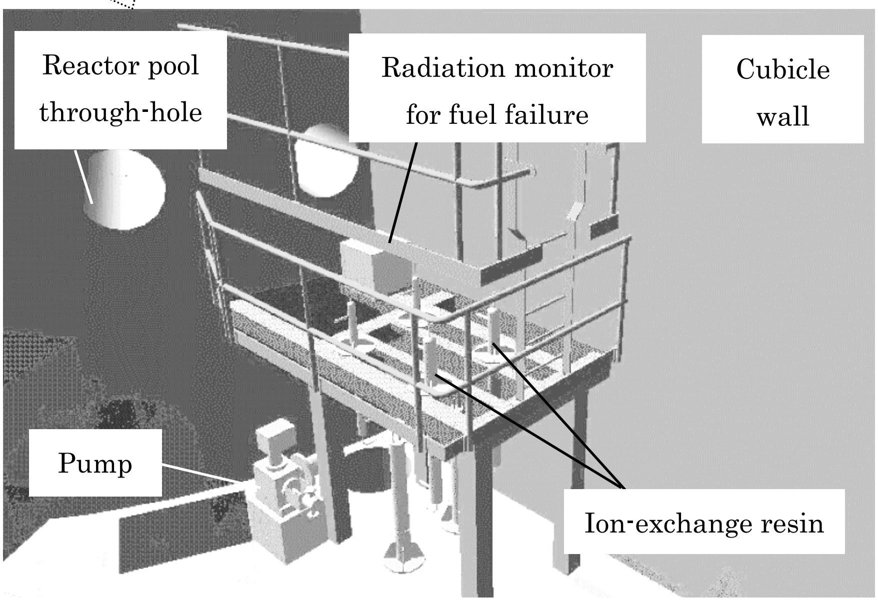
The testing facility for transient fuel behavior to evaluate the safety for the high burn-up light-water reactor fuels (uranium and MOX fuels) has been developed. The facility will be capable of carrying out power ramping and boiling transition tests on light-water reactor fuels.

The testing facility consists of shroud irradiation equipment, capsule control equipment, and He-3 power control equipment. The fabrication design of capsule control equipment was being carried out in 2008, and the procedure of licensing and permission for the test facility construction were carried out. Furthermore, a layout design in the cubicle was performed using results of 3D-laser measurements. The irradiation testing facility is shown in Fig.4.2.1.

These achievements include some of results in the funded project from the Nuclear and Industrial Safety Agency (NISA) in 2008.



(a) Fuel irradiation testing facility



(b) Water purification and chemistry unit

Fig.4.2.1 Outline of fuel irradiation testing facility.

4.2.2 Transient Test Capsule for Fuel

Development of capsules for fuel transient tests have been carried. Purpose of the fuel transient tests is to evaluate the fuel behavior during power ramping condition. In the tests, fuel center temperature and internal pressure, etc. are to be measured. Three types of capsules are designed; fuel-expansion measurement capsule, central temperature and FP gas pressure measurement capsule and heater capsule to correct the fuel linear power. These capsules will be fabricated by 2010. The fabrication design was carried out in 2008, and the procedure of licensing and permission for the capsule construction was carried out. The design specification of fuel transient tests capsule is shown in Table 4.2.2.

For the FP gas pressure gauge, trial fabrication tests using 5MPa and 10MPa sensors were carried out. In the tests, the differential transformer was changed from a ceramic covered wire to a reliable MI cable. As a result of a performance examination at room temperature and 300˚C, the measurement error was ± 1.8% of a full scale. Designed FP gas pressure gage is shown in Fig. 4.2.2.

These achievements include some of results in the funded project from the Nuclear and Industrial Safety Agency (NISA) in 2008.

Table 4.2.2. Design specifications of fuel transient tests capsule.

Items			Condition
OSF-1 Coolant	Operation temperature (inlet)		45 ℃
	Outside surface flow of capsule		About 5 m/s
	Maximum pressure		1.76MPa[gauge]
Maximum heating power of fuel			24 kW
Critical limit	Fall out of sample		< +0.5 %Δk/k
	Insertion and Takeoff of sample		< +0.1 %Δk/k
Seismic intensity	Horizontally		0.6
	Vertically		0.3
Maximum fast neutron fluence (E > 1MeV)			1×10^{26} m^{-2}
Gamma heating rate		D-9 hole	2.5 W/g

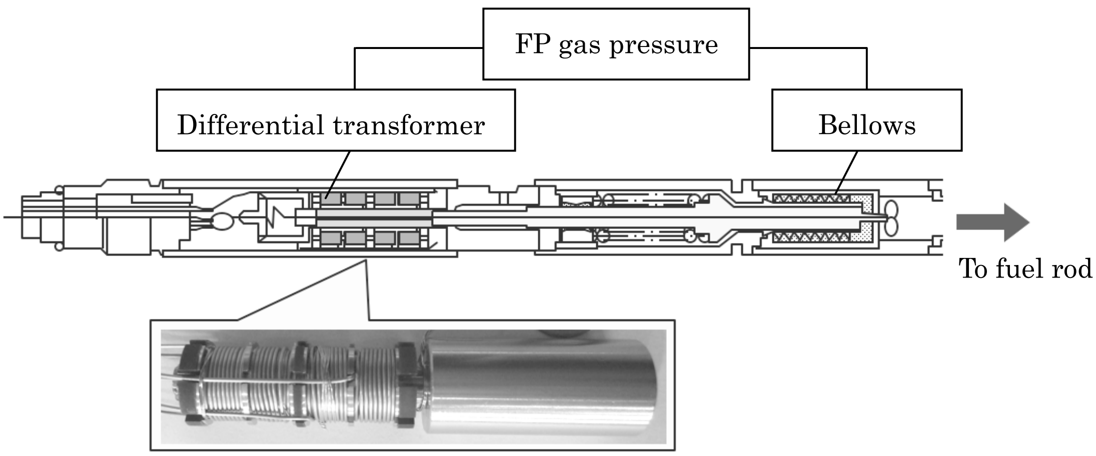


Fig.4.2.2 Outline of FP gas pressure gage.

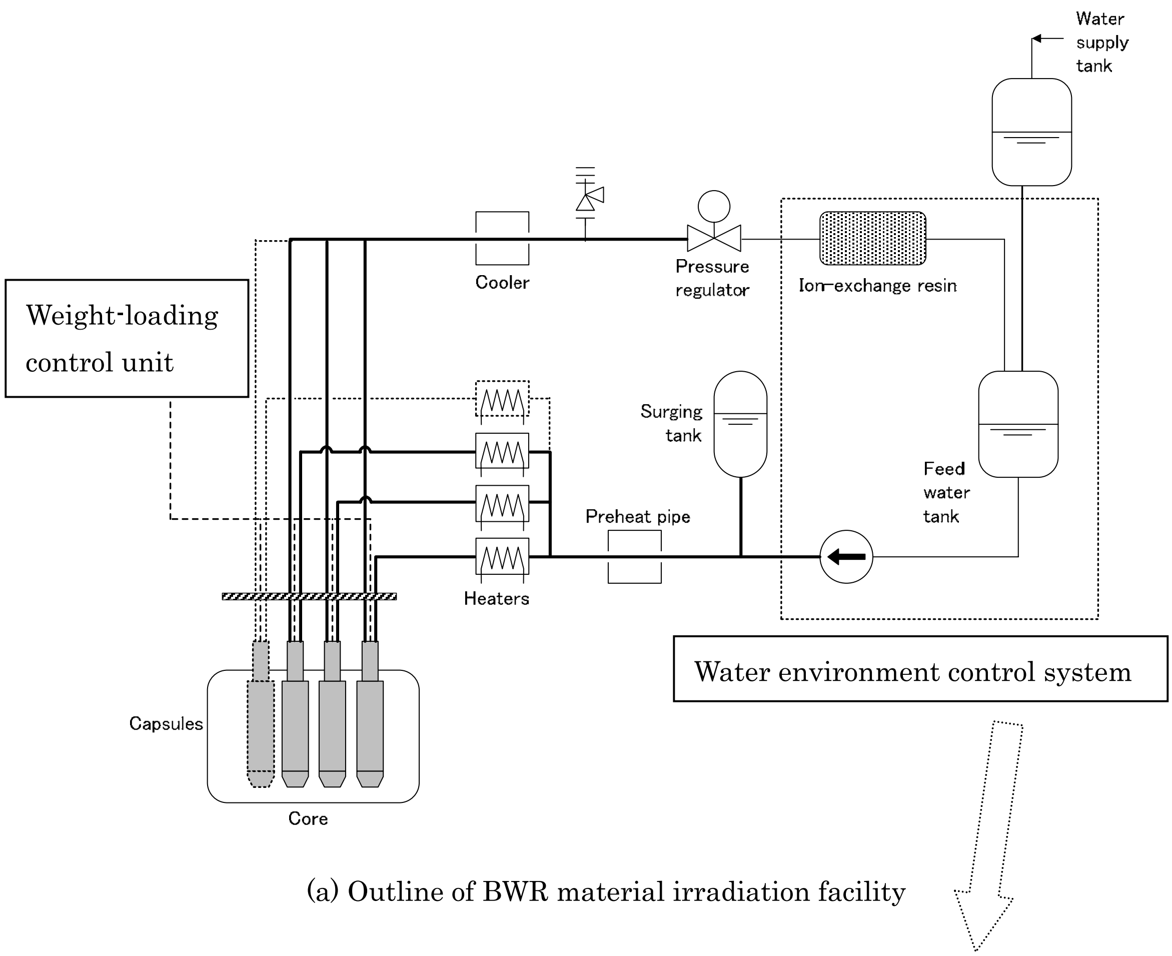
4.2.3 Material Irradiation Facilities

To study the Stress Corrosion Cracking (SCC) under neutron irradiation for the light-water reactor in-core materials, the material irradiation test facility is being developed.

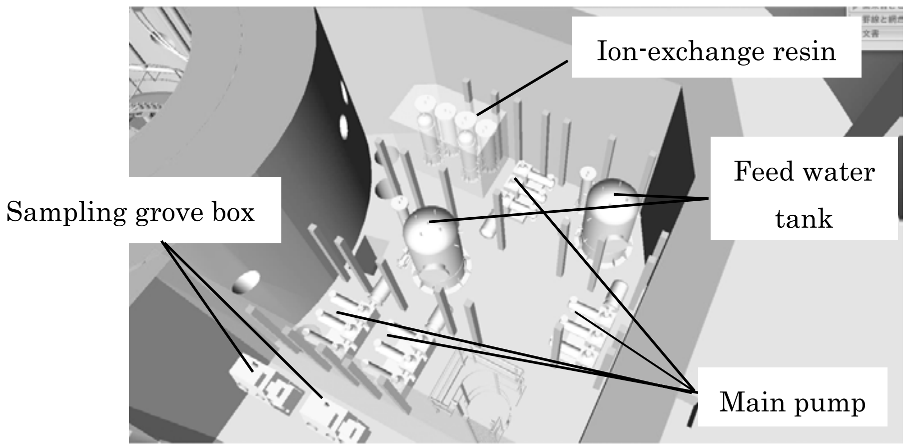
This facility consists of the BWR material irradiation facility simulating the BWR environment and water chemical test facility simulating the BWR and PWR environment. The BWR material irradiation facility consists of a water environment control system, weight-loading control unit and capsules. Outline of BWR material irradiation facility is shown in Fig.4.2.3.

In 2008, the fabrication design of the water environment control system was carried out, and a layout design in the cubicle was also carried out using results of 3D-laser measurements.

These achievements include some of results in the funded project from the Nuclear and Industrial safety Agency (NISA) in 2008.



(a) Outline of BWR material irradiation facility



(b) Water environment control system

Fig.4.2.3 Outline of BWR material irradiation facility.

4.2.4 In-pile SCC Growth Test Unit

The crack growth test units are being developed for the study of Irradiation Assisted Stress Corrosion Cracking (IASCC) under neutron irradiation of austenitic stainless steel components used for light water reactor.

Requirements for the test unit is a high accurate load control as well as measurement of crack length by the terminal-potential-difference method.

Moreover, it is indispensable to use large size specimens to obtain valid data from a viewpoint of the fracture mechanics consideration. Therefore, for the in-core crack growth test technique, it is necessary to develop a new loading technique, which is applicable to compact tension (CT) specimens with thickness of 0.5 inch (0.5T).

From a mock-up test, it is expected that a target load can apply to the 0.5T-CT specimen, and that the crack length can measure by the test unit with a lever type structure instead of the previous uni-axial tension type structure. Developed prototype mock-up unit for the crack growth test is shown in Fig.4.2.4. Several investigations in out-pile tests using the developed mock-up unit will be carried out in near future, and results would be reflected in the unit for in-pile tests.

These achievements include some of results in the funded project from the Nuclear and Industrial safety Agency (NISA) in 2008.

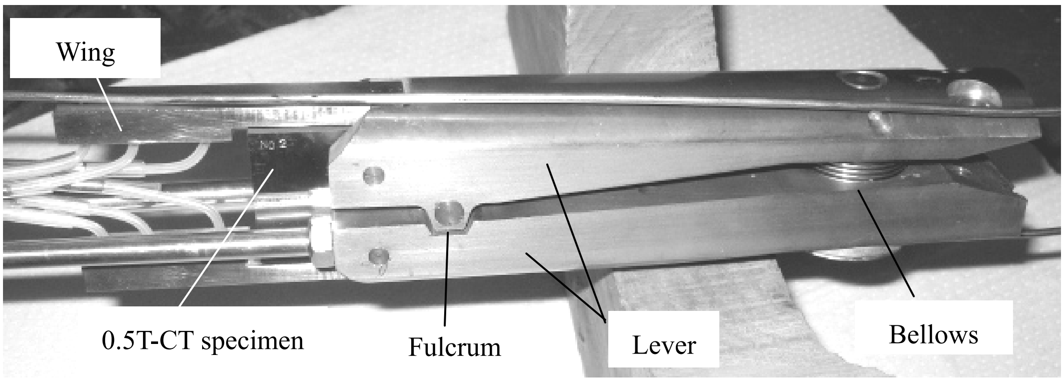


Fig.4.2.4 Prototype mock-up unit of crack growth test.

4.2.5 ECP Sensor

To measure the water chemistry condition for a light-water reactor, the Electrochemical Corrosion Potential (ECP) sensor, which has the durability under the irradiation, has been developed.

Trial fabrication tests using the sensor mock-ups (without the internal structure) were performed in this year. The mock-ups were fabricated to simulate real shape by brazing with stabilized zirconia and 42 alloys. For joining shape, A type (conventional type) and S type, which could reduce the residual stress at the joint rather than that of A type, were selected. The mock-ups of A type and S type are shown in Fig.4.2.5. In addition, matching structure (T type, 8 mm outside diameter, 4 mm inside diameter) with the stabilized zirconia and SUS430 was also selected because residual stress might decrease in the evaluation of last year. As a result, the soundness of 3 of 3 mock-ups for A type, 1 of 2 mock-ups for S type and 2 of 2 mock-ups for T type was confirmed by pressure tests.

These achievements include some of results in the funded project from the Nuclear and Industrial safety Agency (NISA) in 2008.

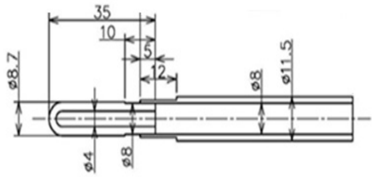
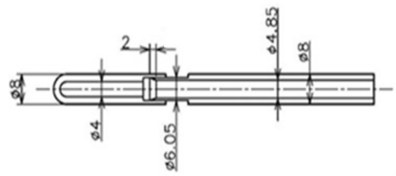
A type (conventional type)	Structure of A type
	
S type	Structure of S type
	

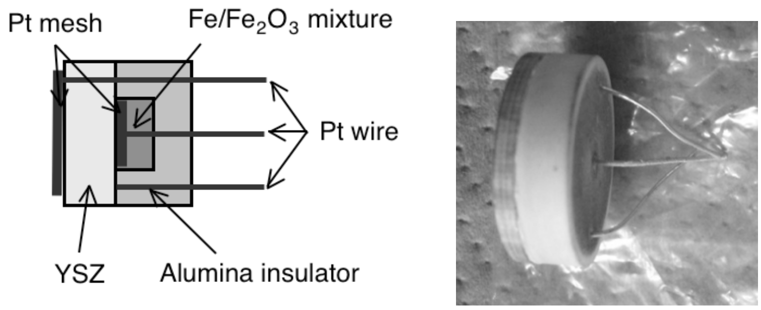
Fig.4.2.5 ECP sensor mock-ups for A and S type.

4.3 Irradiation Technology for Advanced Instrumentation

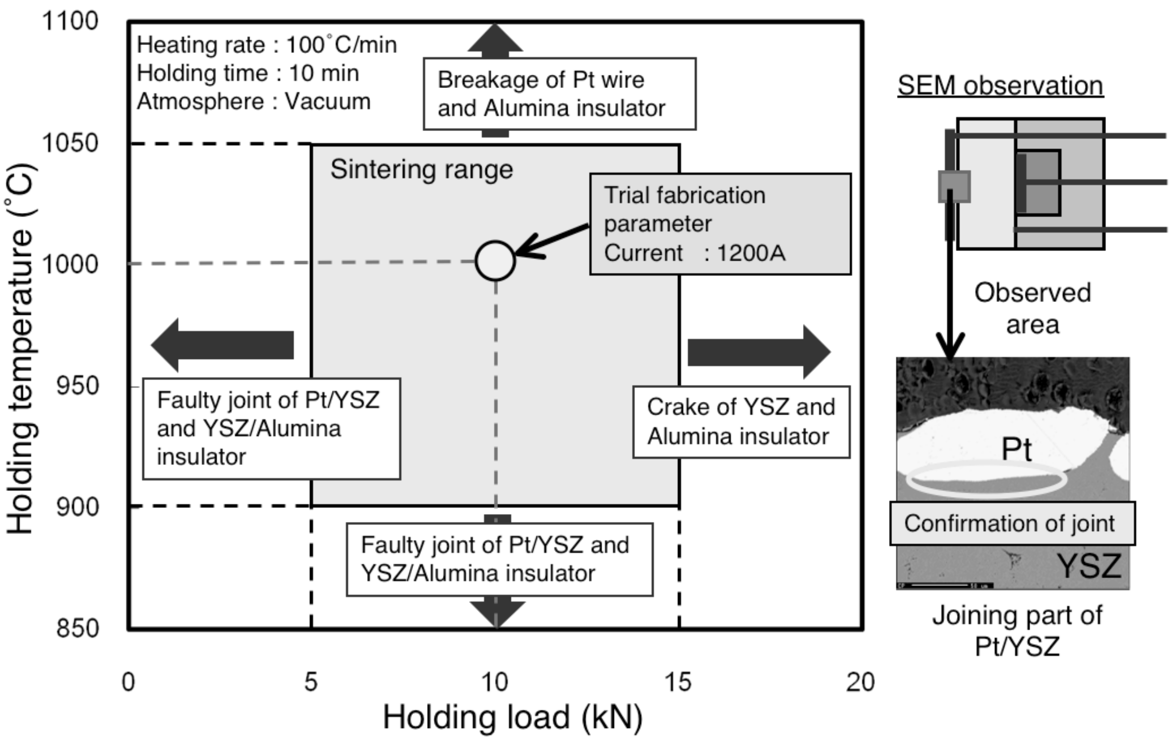
4.3.1 Ceramics oxygen sensor

It is important for neutron irradiation test of materials and fuels to clarify the irradiation environment. For example, the oxygen and hydrogen peroxide concentrations are required to measure in the analysis of corrosion mechanism of the structure materials under light-water reactor conditions. It is also necessary to develop the small and high-accuracy sensor, because the outer diameter of the irradiation capsule used in JMTR is limited below ϕ 65 mm. Thus, the small ceramics oxygen sensor combined stabilized-zirconia (YSZ) as oxygen ion conductor and platinum as electrode has been developed.

In this year, the trial fabrication test of the ceramics oxygen sensor was carried out with the Spark Plasma Sintering (SPS) method. In this test, sintering temperature and load were studied for the fabrication of the sintered samples combined alumina insulator, YSZ and Pt wire. Structure of ceramic oxygen sensor and relationship of the sintering temperature and load are shown in Fig.4.3.1. Results of the study suggested the prospect of the ceramic oxygen sensor fabricated by the SPS method.



(a) Structure of ceramic oxygen sensor



(b) Relationship of sintering temperature and load.

Fig.4.3.1 Results of trial fabrication test of the ceramics oxygen sensor.

4.3.2 ^{99}Mo Production Technology by Mo Solution Irradiation Method

The solution irradiation method is proposed as a new production technique for ^{99}Mo, which is the parent nuclide of ^{99m}Tc used as a radiopharmaceutical. In this new method, an aqueous molybdenum solution is irradiated with neutrons in a nuclear reactor. Efficient and low-cost ^{99}Mo production compared with conventional ^{99}Mo production can be realized by the ^{98}Mo (n, γ) ^{99}Mo reaction and the molybdenum adsorbent of Poly-Zirconium Compound (PZC).

As a result of the last year, it was found that an aqueous potassium molybdate solution is a good irradiation target in terms of the dissolved molybdenum in the solution and the chemical stability of the solution. Moreover, it was also found that the stainless steel has a potential as the structural material of capsules, pipes and so on because of its good compatibility with the solution.

In this year, the properties of the aqueous potassium molybdate solution were measured, and the activation analysis of the aqueous potassium molybdate solution after gamma-ray irradiation tests was carried out. In addition, testing apparatus for a long-term corrosion test was made.

As for the activation analysis, Na and W were detected as impurities in the solution. Na, which has high gamma-ray energy, affects shielding design. As for the long-term corrosion test, two types of the test apparatus were made; the one is used for the static solution, and the other is used for the circulating solution. The schematic diagram of the test apparatus using the circulating solution is shown in Fig.4.3.2.

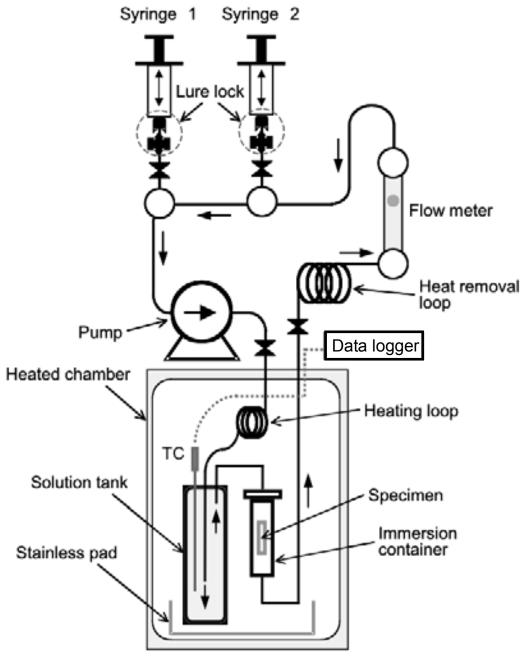


Fig.4.3.2 Test apparatus of circulating solution type for the long-term corrosion.

4.3.3 Beryllium Recycling Technology

Beryllium has been used as a moderator and/or reflector in JMTR because of its low neutron capture and high neutron scattering cross sections. However, it is necessary to exchange the beryllium frame within every fixed period, and the frame was exchanged five times up to 165th cycle in 2006. Thus, the lifetime expansion of the beryllium frame has been studied to increase in the reactor available factor and to decrease in the irradiated beryllium waste.

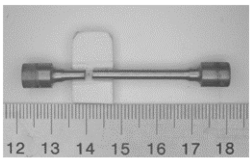
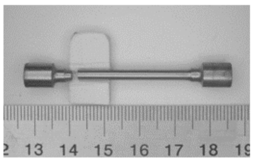
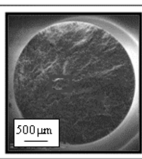
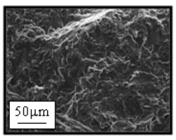
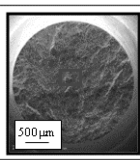
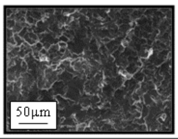
Preliminary irradiation test was performed from 162nd to 165th cycles, and the effects on mechanical properties of two kinds of beryllium metals (see Table 4.3.3) were evaluated.

The tensile properties of S-65C were almost similar to those of S-200F at room temperature and 200°C. The tensile strength of the S-65C irradiated up to $1.5\times10^{25}/m^2$ (E>1MeV) was larger than that of the irradiated S-200F (see Fig.4.3.3). These irradiation data are utilized for the material selection for the lifetime expansion.

On the other hand, recycling technology of irradiated beryllium was approved as the International Science and Technology Center (ISTC) project on Oct., 2008. The transportation procedure from Japan to Kazakhstan for the irradiated beryllium has been started.

Table 4.3.3 Properties of beryllium metals for preliminary irradiation test.

Beryllium Grade	S-200F	S-65C
Fabrication method	VHP(Vacuum Hot press)	
Mechanical properties		
Tensile strength (MPa)	339	330
0.2% yield strength (MPa)	265	255
Elongation (%)	3.9	3.7
Elements (wt%)		
Be	99.1	99.4
BeO	**1.1**	**0.7**
Al	0.04	0.02
C	–	–
Fe	0.10	0.06
Mg	0.013	< 0.01
Si	0.03	0.03
Other elements	–	–

	S-65C	S-200F
Tensile test condition	25°C, Air atmosphere	25°C, Air atmosphere
Fracture strength	392 MPa (av.)	344 MPa (av.)
Elongation	2.8%	2.4%
Aspect of specimen after tensile test		
SEM photograph of fracture surface	 	 

[Irradiation condition] Irr. Temperature: ~50°C (water temperature), Neutron Fluence: $1.5\times10^{25}\,m^{-2}$ (E>1.0MeV)

Fig.4.3.3 Results of tensile test.

4.4 Improvement of Neutronic Evaluation for JMTR

In the evaluation of irradiation field of JMTR for irradiation tests, calculated neutron flux/fluence were verified the measured data by irradiation fluence monitors. Regarding the gamma dose, calculated gamma heating rate was verified the measured data by the nuclear heating evaluation capsule, which was developed to measure the nuclear heating rate. It was confirmed that the calculated fast and thermal neutron flux/fluence agreed with measurements within ±10%, ±30%, respectively, and that the calculated gamma dose agreed within -3～14%.

Although the accuracy is common in the irradiation testing reactors in the world, only the evaluation accuracy of a thermal neutron flux has not been improved up to a fast neutron flux level; namely, the thermal neutron flux has so far been permitted.

Therefore, to achieve high accuracy of neutronic evaluation, especially for the thermal neutron flux from ±30% to ±10%, an improvement study is conducted to offer high-technical-value data to JMTR users.

Fast and thermal neutronic calculations are conducted using the Monte Carlo code MCNP(Ver.4B) with continuous energy neutron cross section library FSXLIBJ3R2 (derived from JENDL3.2) and thermal S(α, β) libraries of ENDF-B/III.

The accuracy of calculated fast and thermal neutron flux was examined from a viewpoint of irradiation region in the JMTR core. As a result, calculated thermal neutron flux tends to overestimate in the beryllium reflector layer 2 and the aluminum reflector layer 1 in comparison with the other irradiation regions. However, calculated fast neutron flux has no dependence on irradiation region (Fig.4.4.1 and Fig.4.4.2).

It was found that the accuracy of thermal neutron flux was perhaps relevant to the neutron scattering and absorption process in thermal energy region. Therefore, examination for neutron scattering and absorption process in thermal energy region are to be performed.

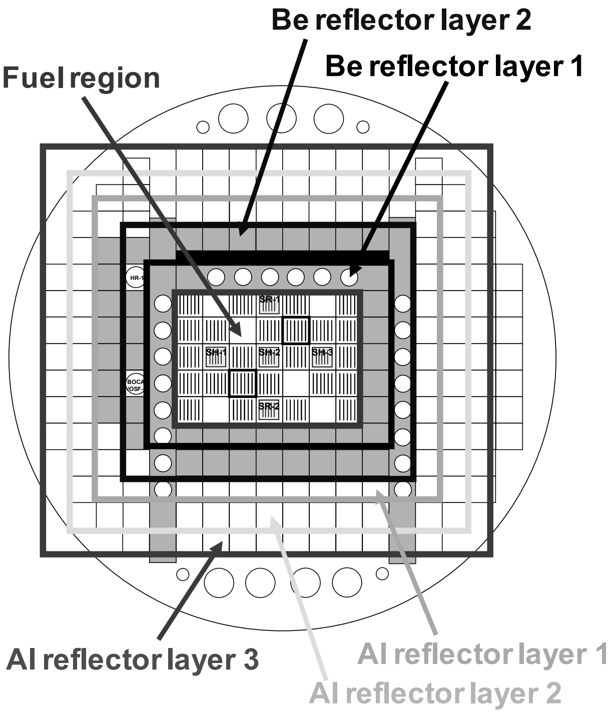


Fig.4.4.1 Core configuration of JMTR

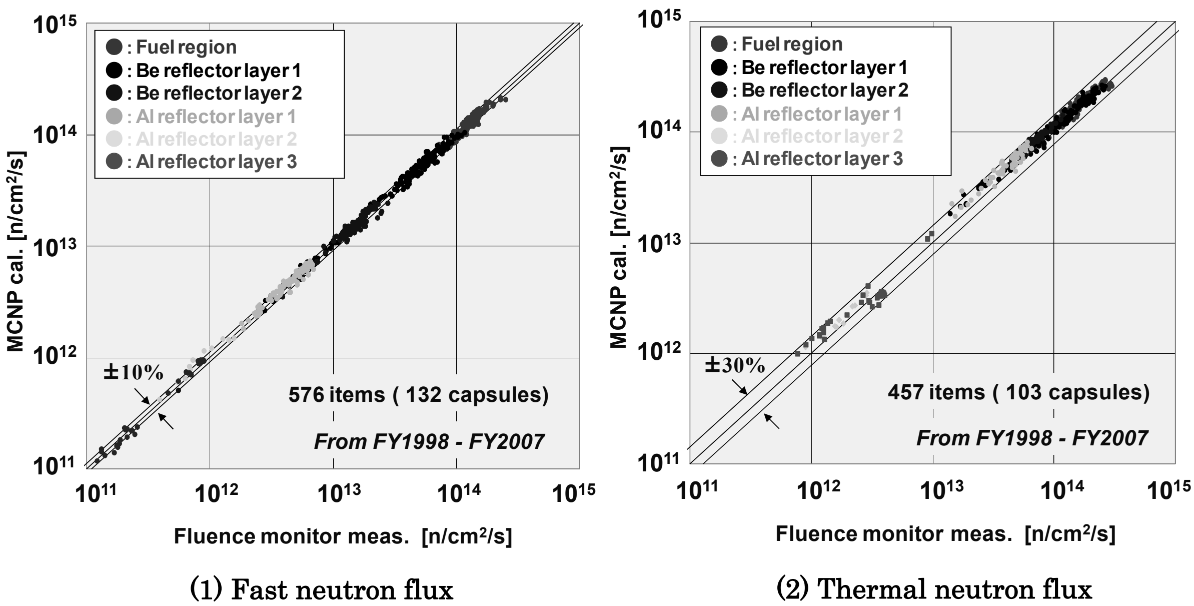


Fig.4.4.2 Current evaluation of neutron flux.

5. International Cooperation

5.1 Construction of World Network on Materials Testing Reactors

To establish an international network on irradiation test reactors, the "International Symposium on Materials Testing Reactors" hosted by JAEA was held on July 16 to 17, 2008, at the Oarai Research and Development Center (Fig.5.1.1). There were 138 participants from Argentina, Belgium, France, Indonesia, Kazakhstan, Korea, the Russian Federation, Sweden, the United State, Vietnam and also from Japan.

The objective of the symposium is to exchange information on status and future plan of materials testing reactors, irradiation technology, etc. to make a mutual understanding. The symposium was divided into four technical sessions by oral presentations and three topical sessions by panel discussions. From discussions by participants, importance of the information exchange on basic irradiation technology was recognized, and the necessity of the construction of the network was also recognized. Participants also requested the next symposium to be held on autumn of 2009 in the United State (Idaho National Laboratory) to continue discussions on these issues.

Moreover, aiming at the establishment of Asian network on irradiation test reactors, information exchange was carried out by short visiting from KAERI (Korea Atomic Energy Research Institute), based on a post-irradiation test program between the JAEA-KAERI cooperation. Furthermore, researchers from the NITRC (Neutron Irradiation and Testing Reactor Center) were dispatched to Malaysia and Indonesia to exchange information on irradiation technology and PIE (Post-Irradiation Examination) technology.

Fig.5.1.1 International symposium on material testing reactors.

5.2 Cooperation Research with Korea Atomic Energy Research Institute

As the international cooperation between JAEA and KAERI, information exchange in the field of reactor operation management, utilization, irradiation technology, and PIE technology is under way.

In FY 2008, related to these research cooperation fields, the "2008 KAERI-JAEA Joint Seminar on Advanced Irradiation and PIE Technologies" has been held at KAERI in Daejeon, Korea, from November 5 to 7, 2008.

This is a sixth triennial seminar started from 1992. Active and valuable information exchanges were done with a total of 46 presentations by a total number of 113 participants including 13 participants from JAEA. Here, the fifth seminar was held in JAEA (Oarai Research and Development Center) in 2005.

5.3 Cooperation Research with Studsvik AB

Based on the implemental agreement between the Studsvik AB and JAEA for cooperation in nuclear energy research and development, the first annual meeting was held at Oarai Research and Development Center, JAEA, on July 18, 2008. In this meeting, information exchange on two cooperation areas, "Radioactive waste treatment technology including recycling of materials" and "Technical developments for the neutron irradiation experiments in materials testing reactors", was carried out, and the future cooperation plan was discussed.

5.4 Cooperation Research with Kazakhstan National Nuclear Center

Based on the memorandum between the JAEA and Kazakhstan National Nuclear Center (NNC) for the future cooperation in nuclear research and development, information exchange for nuclear technology on test and research reactors was carried out at Institute of Nuclear Physics(INP), NNC, Almaty from April 14 to 15, 2008.

Furthermore, agreement for cooperation research and development between the JAEA and Kazakhstan NNC in a nuclear science field was concluded on February 2, 2009, and the cooperation for nuclear technology on test and research reactor was started.

6. Conclusions

In FY 2008, renewal works for reactor facilities and preparation works for irradiation facilities are carried out as scheduled to restart of JMTR from FY 2011. Moreover, the attempt to improve the accuracy of calculated irradiation parameters and the development of irradiation facilities for an aging management of LWRs were conducted to obtain valuable irradiation data by high irradiation technologies. From an usability improvement, a feasibility study to improve reactor operation rate of JMTR, etc. were also conducted. Aiming at the establishment of international center with internationally utilized base as an Asian center of testing reactors is under consideration.

From FY 2009, an application for utilization of JMTR is to be started, and preparation for restart of JMTR will move into a higher gear. The Center highly appreciates the reader's expectations and support toward the refurbishment and restart of the JMTR.

Acknowledgement

The authors wish to thank Mr. Nozomu Fujimoto, general manager of HTTR Operation Section, for his useful discussions to publish this report.

Appendix 1 Renewal of Reactor Facilities

The reactor facilities in JMTR are to be refurbished during four years from the beginning of FY 2007. The reactor facilities to be renewed are the reactor instrument-and-control system, reactor cooling system, radioactive waste facility, power supply system, etc. The renewal of the air conditioning system and the degassing demineralizer was already completed in FY 2007.

In FY 2008, renewal works of reactor cooling system, radioactive waste facility, power supply system, etc. were carried out as scheduled, and applications of the regulatory approval, i.e. the renewal of beryllium-frame, gamma-shield, primary cooling system, secondary cooling system, feed-and-exhaust air system, were completed up to March 2009.

From FY 2009, the instrument-and-control system (reactor control system, process control system, the nuclear instrumentation system and the control rod drive mechanism), the primary cooling system (the motors of primary pumps, the transfer pumps, the charging pumps, etc.), the secondary system (the circulating pumps, auxiliary pumps, etc.), the radioactive waste facility (the drainage system) and so on are to be renewed.

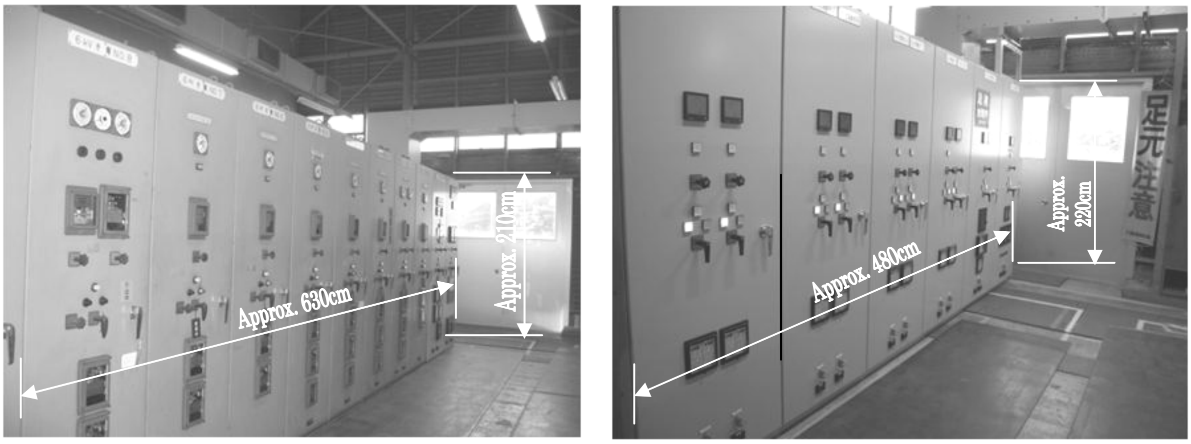
Main renewed reactor facilities from FY 2007 to FY 2008 and under renewing reactor facilities are as follows.

1. Renewed Reactor Facilities

(1) Power Supply System

The renewal design for the power supply system was started at FY 2007. From April 2008 to January 2009, after the existing equipments, such as power panels, the high-voltage transformers, the cables, were removed, renewal equipments were transported and installed. Renewal of power panels and high-voltage transformers are shown in Fig.A-1 and Fig.A-2.

Maintenance and reliability of power panels were improved by miniaturization, digitization of relays and dehumidifier installation into a board for dew prevention. As for cables, the existing CV cables were replaced with flame-resistant cables to improve the safety to fire.



(Before renewal) (After renewal)

Fig.A-1 Renewal of power panels.

(Before renewal) (After renewal)

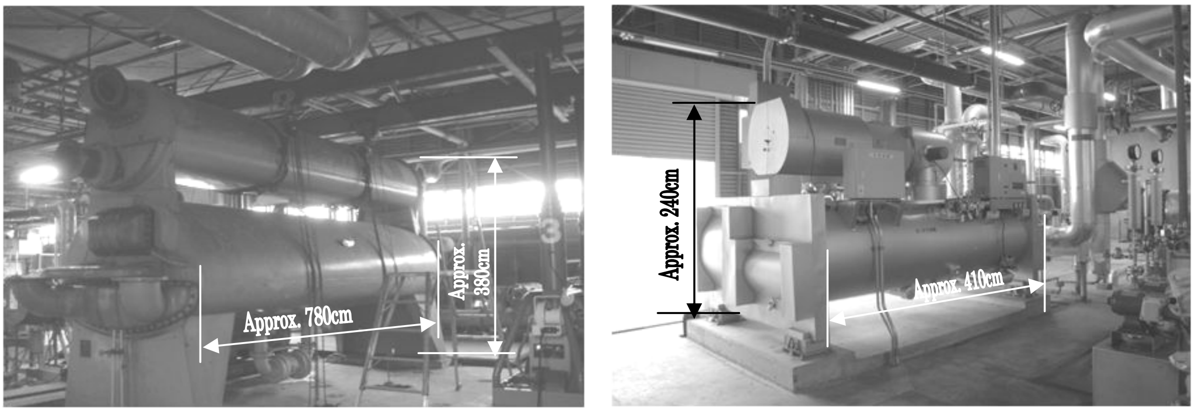
Fig.A-2 Renewal of high-voltage transformers.

(2) Air conditioning system and boiler

The absorption chiller for the air conditioning in the reactor building and the boiler for heating and cooling, which had been continuously used for about 40 years, were renewed, since it becomes difficult to get spare parts.

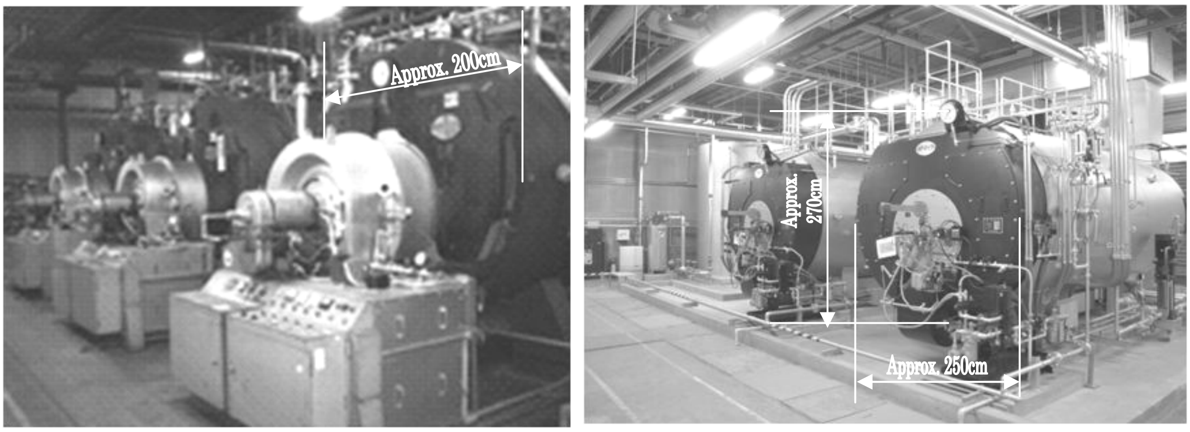
The absorption chiller was replaced with the centrifugal chiller which does not need the heat from a boiler, so that the heavy oil cost by the boiler operation in summer can be reduced about 40% from the former type. In addition, the centrifugal chiller is a excellent machined with fine adjustable operation time as well as easy maintenance from its simple structure. Renewal of the air conditioning system is shown in Fig.A-3.

In the renewal of boilers, the number of boilers was changed into two sets from four sets by enlargement of the heat transfer area per boiler on the basis of a review of required capacity after restart of JMTR. Renewal of boilers is shown in Fig.A-4.



(Before renewal) (After renewal)

Fig.A-3 Renewal of air conditioning system.



(Before renewal) (After renewal)

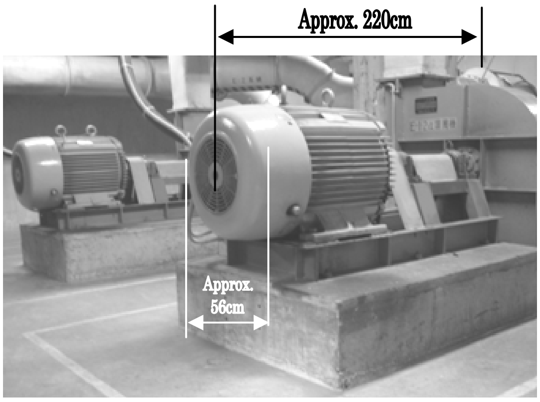
Fig.A-4 Renewal of boilers

(3) Radioactive waste facility

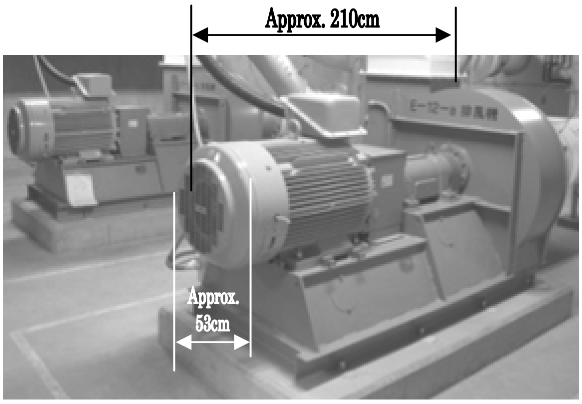
The feed-and-exhaust air system in the radioactive waste facility (exhaust blower, control circuit, etc.) were renewed. Replaced parts are the emergency exhaust blower fans and motors, driven section of butterfly valves in a feed air line, butterfly valve in a exhaust air line and exhaust air duct.

In the renewal of the motor in the air blower for sending air into the reactor building, the existing rotor-type motor was replaced with the basket-shaped motor to improve the maintenance. Structure of the basket-shaped motor is simple and robust compared with the rotor-type motor. Since the rotor in the basket-shaped motor has no insulating member and has a heat-resistant structure, it is strong to the electrical overload in high velocity revolution region. Furthermore, its rotor has no brush nor a collector ring which causes wear, then the easy maintenance and operation management can be improved.

In the renewal of the control circuit, existing power relay circuit was replaced with a sequencer circuit. Small component parts of the sequencer circuit compared with that of the existing one will improve the maintenance and operation management activities with reduction of failure. Renewal of the emergency exhaust blowers is shown in Fig.A-5.



(Before renewal)



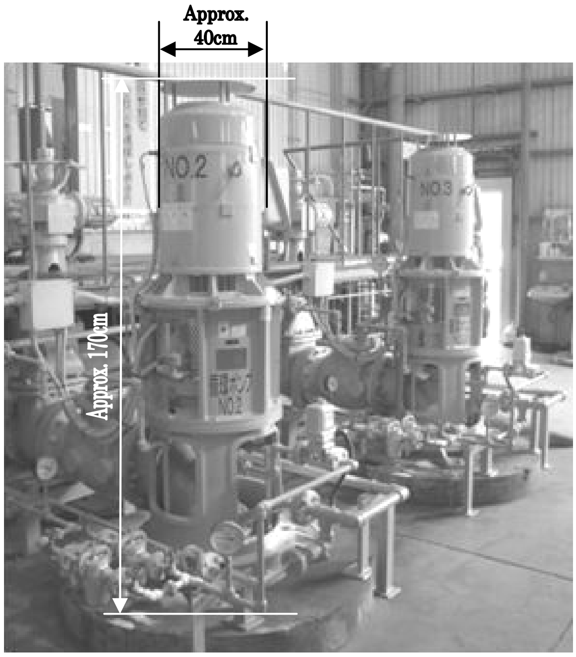
(After renewal)

Fig.A-5 Renewal of emergency exhaust blowers.

(4) Reactor cooling system

In the renewal of UCL (Utilities Cooling Loop) system in the reactor cooling system, motors in a circulating pump and a storage pump, outlet valves in a storage pump, the motors and the decelerator in a cooling tower fan, etc. were renewed. Since these equipments had been also used since the construction of the JMTR, these were renewed with the same performance as existing ones to improve the maintenance and reliability. Renewal of circulating pumps in the UCL system is shown in Fig.A-6.

(Before renewal)



(After renewal)

Fig.A-6 Renewal of circulating pumps in UCL system.

2. Under renewing reactor facilities

(1) Instrument-and-control system

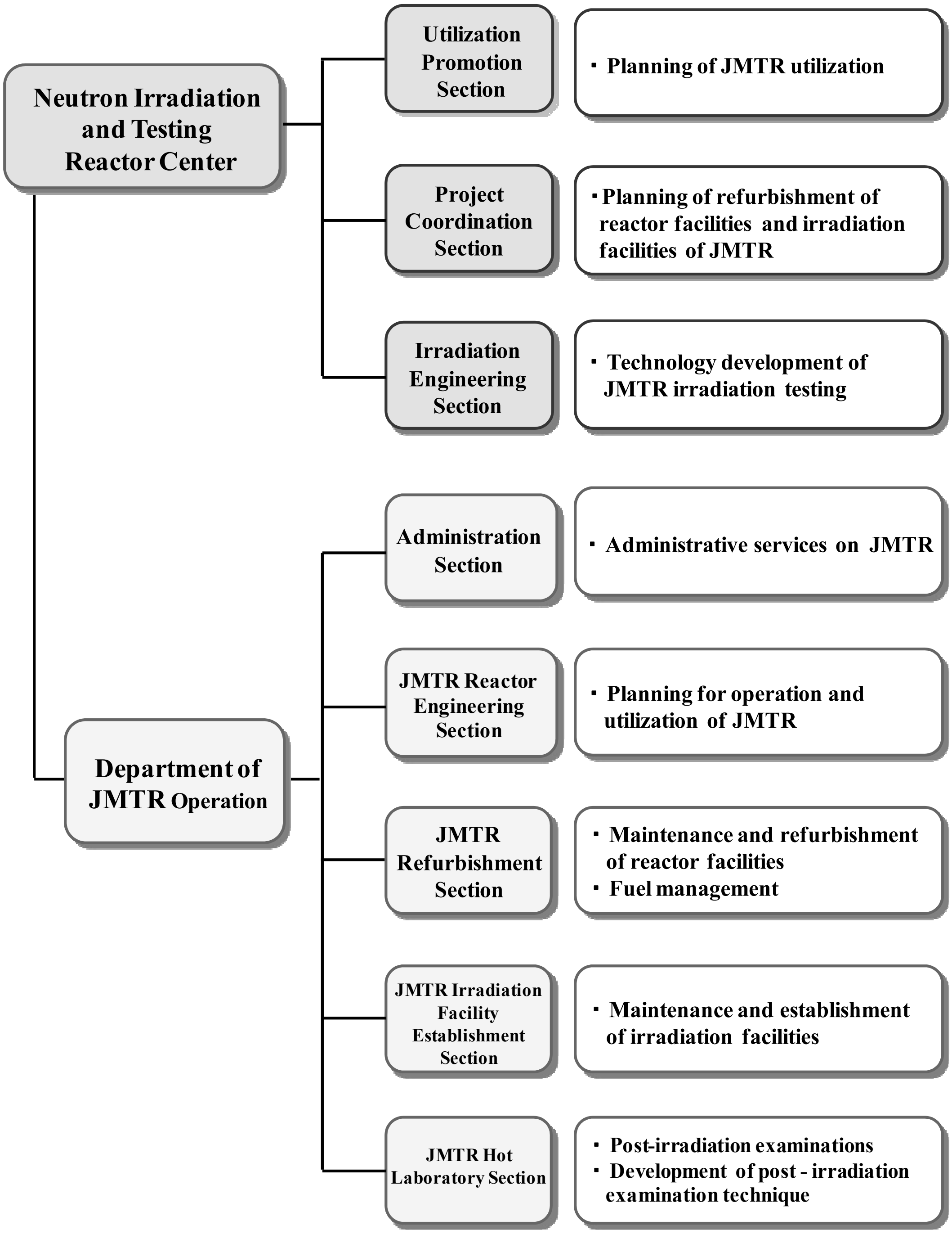
The reactor control system, the process control system, the nuclear instrumentation system and the control rod drive mechanism in the instrument-and-control system are to be renewed. Their circuits consist of a huge amount of relays and soldered wirings, and they will be replaced by present-designed integrated circuits to improve the reliability. Moreover, indicators, switches, etc. in these systems are classified and arranged at every function, and are designed from a viewpoint of improvement of man-machine interface so as to be able to operate reactor more easily and visually. Install of pre-amplifier in start-up channels and renewal of the earth wire in the nuclear instrumentation system are to be carried out to protect noises, and the instrumentation system was modularized to reduce loose electrical connection to improve the reliability. In the renewal of the control rod drive mechanism, the fundamental structure is not to be replaced, however reed switches, electromagnet, ball screw in the control rod drive mechanism are replaced to improve the reliability and maintenance management.

(2) Reactor cooling system

The primary cooling system had been used since the construction of the JMTR except for the renewal in some parts such as main pump piping, valves and modification of a support structure of piping in pump bypass line. The equipments to be renewed in primary cooling system are the motors of primary motor, the charging pump and its motor, the transfer pump and its pump, the actuator of main valves, the electromagnetic coil of reactor pool connecting valve, etc. These equipments are to be renewed with the same performance as existing ones to improve the maintenance management.

The secondary cooling system had been also used since the construction of the JMTR except for the renewal in some parts such as valves, cooling tower fan, cooling tower. The equipments to be renewed in the secondary cooling system are the motors in a circulating pump and auxiliary pump, main diaphragm valves, the motors and the decelerator of cooling tower fan, etc. These equipments are to be renewed with the same performance as existing ones to improve the reliability and maintenance management.

Appendix 2 Organization of the Neutron Irradiation and Testing Reactor Center



Appendix 3 Maintenance and Management of JMTR

1. Maintenance and Management of JMTR Reactor Facility

The JMTR reactor facility can be classified into three main categories: the reactor section, the irradiation section, and the auxiliary section. The reactor section includes the reactor building, reactor core, and primary cooling system. The irradiation section includes irradiation-related equipments, while the auxiliary section includes reactor utilities.

The regular self-inspection to the reactor facility was performed from July to December, 2008, and confirmed the sustained reactor performance and functions of the JMTR.

The regular mandatory-inspection was carried out to reactor facilities which are required to keep their function during the halt. Two days inspection from December 17 to 18, 2008 was carried out by inspectors from the MEXT (Ministry of Education, Culture, Sports, Science and Technology), similar to the 2007 mandatory-inspection. From the inspection, the maintained performance of the reactor was verified.

2. Maintenance and Management of Hot Laboratory Facility

2.1 Operation and Management

Since 1970, a wide variety of post-irradiation tests have been carried out in the hot laboratory located adjacent to the reactor. Irradiated samples in the JMTR reactor were tested destructively as well as nondestructively for the purpose of research and development of nuclear fuels and materials. The hot laboratory also managed the shipment of RI materials.

Hot cells are separated into three main lines; concrete cells (ß・γ-cells) including microscope lead cells, lead cells for material testing, and steel cells.

In 2008, 42 capsules were dismantled to post-irradiation tests, and post-irradiation tests for 13 capsules among them have completed.

2.2 Maintenance and Management

The hot laboratory facility is divided into two sections; the main section comprises the hot cell and hot laboratory building, and the auxiliary section relating to the hot laboratory utilities. The regular self-inspection to the facility was conducted from August 2008 to February 2009, and performance and functions for the hot laboratory was confirmed to be sustain.

Appendix 4 Reports on Annual Activities

Contributions to conference

1. H. Kawamura, "RI Production and Supplement with Research and Testing Reactor", 45th Isotope/Radioactive Rays Meeting for Presenting Research, (2008).

2. Y. Hanakawa, et al., "Preliminary Inspection of Secondary Cooling System Piping for Maintenance Plan in JMTR", Annual Meeting of Japan Society of Maintenology, (2008).

3. K. Iimura, et al., "Conceptual Plan of Radiopharmaceutical Production Process in JMTR", FAPIG, (2009).

4. N. Takemoto, et al., "Refurbishment status of JMTR", Symposium on Operation, Maintenance and Improvement for the Research Reactor, Yayoi, Tokyo Univ., UTNL-R0471, pp. 511-518, (2009).

5. Y. Hanawa, et al., "Replacement of Beryllium Reflector", Symposium on Operation, Maintenance and Improvement for the Research Reactor, Yayoi, Tokyo Univ., UTNL-R0471, pp. 521-528, (2009).

6. T. Kimura, et al., "Investigation of Waste Disposal Procedure of Spent Ion Exchange Resin", Symposium on Operation, Maintenance and Improvement for the Research Reactor, Yayoi, Tokyo Univ., UTNL-R0471, pp. 531-5310, (2009).

7. Y. Onuma, et al., "Decommissioning Study of Water Loop Irradiation Facility", Symposium on Operation, Maintenance and Improvement for the Research Reactor, Yayoi, Tokyo Univ., UTNL-R0471, pp. 541-547, (2009).

8. M. Ogawa, et al., "Creating a database of Irradiation Facilities troubles", Symposium on Operation, Maintenance and Improvement for the Research Reactor, Yayoi, Tokyo Univ., UTNL-R0471, pp. 551-5511, (2009).

9. M. Yonekawa, et al., "Current state of PIE technology", Symposium on Operation, Maintenance and Improvement for the Research Reactor, Yayoi, Tokyo Univ., UTNL-R0471, pp. 561-567, (2009).

10. T. Taguchi, et al., "Post-irradiation examination techniques for research on behavior of IASCC", Symposium on Operation, Maintenance and Improvement for the Research Reactor, Yayoi, Tokyo Univ., UTNL-R0471, pp. 571-578, (2009).

11. N. Hori, et al., "Refurbishment and Restart of JMTR (1) Present Status and Future Plan of JMTR", Annual Meeting of Japan Atomic Energy Society, (2009).

12. Y. Hanakawa, et al., “Refurbishment and Restart of JMTR (2) Study on Renewal of Aging Reactor Component”, Annual Meeting of Japan Atomic Energy Society, (2009).

13. N. Takemoto, et al., “Refurbishment and Restart of JMTR (3) Study on Core Management Techniques for Achievement of High Reactor-availability-Factor”, Annual Meeting of Japan Atomic Energy Society, (2009).

14. K. Izumo, et al., “Refurbishment and Restart of JMTR (4) Design of Mo-99 Production Process using Pellet”, Annual Meeting of Japan Atomic Energy Society, (2009).

15. K. Tsuchiya, et al., “Refurbishment and Restart of JMTR (5) Technology Development on Recycling of Beryllium Reflectors”, Annual Meeting of Japan Atomic Energy Society, (2009).

16. S. Kitagishi, et al., “Refurbishment and Restart of JMTR (6) Development of In-situ Sensing Technology under Corrosion Environment”, Annual Meeting of Japan Atomic Energy Society, (2009).

17. Y. Inaba, et al., “Refurbishment and Restart of JMTR (7) Technology Development on the Advanced ^{99}Mo Production by Solution Irradiation Method”, Annual Meeting of Japan Atomic Energy Society, (2009).

18. Y. Nagao, et al., “Refurbishment and Restart of JMTR (8) Improvement of Neutronic Evaluation for JMTR”, Annual Meeting of Japan Atomic Energy Society, (2009).

19. Y. Matsui, et al., “R&D Project on Irradiation Damage Management Technology for Structural Materials of Long-life Nuclear Plant (2) Reports of Coupling Irradiation (JRR-3 and JOYO) and Hot Facilities Work (WASTEF, JMTR-HL, MMF and FMF)”, Annual Meeting of Japan Atomic Energy Society, (2009).

20. F. Takada, et al., “Research and Development Project Irradiation Damage Management Technology for Structural Materials of Long-life Nuclear Plant (4) Post Irradiation Examination of Combinative Irradiated Material by Remote Control Type Micro Creep Test Apparatus”, Annual Meeting of Japan Atomic Energy Society, (2009).

Papers

1. Y. Nagao, M, Niimi, H. Kawamura, T. Iguchi*, "Improvement of Neutron/Gamma Field Evaluation for Restart of JMTR", Proc. of 13th International Symposium on Reactor Dosimetry, (2008).

2. A. Shibata, J. Nakano, M. Ohmi, K. Kawamata, T. Saito, K. Hayashi, J. Saito, T. Nakagawa, T. Tsukada, "Technical Development for IASCC Irradiation Experiments at the JMTR", Proceedings of 16th International Conference on Nuclear Engineering (ICONE-16), (2008).

3. H. Kawamura, N, Hori, "Production and Research Development of Radioisotope with Research and Testing Reactors of JAEA I. The Present Condition of Supply Future Plan", ISOTOPE NEWS, No.650, pp. 6-11, (2008).

4. N. Hori, K. Izumo, Y. Nagao, M. Niimi, H. Kawamura "Outline of JMTR Refurbishment Status", Proceedings of International Conference of Nuclear Power of Republic Kazakhstan, (2008).

5. Y. Inaba, K. Ishikawa, T. Ishida, K. Kurosawa*, Y. Hishinuma*, K. Tadenuma*, E. Ishitsuka, "Proc. of Preliminary Study on ^{99}Mo Production Method by Irradiation of Circulating Molybdenum Solution", Nuclear Power Engineering in Kazakhstan NP-2008, (2008).

6. K. Tsuchiya, G. Longhurst*, V. Chakin*, I. Tazhibayeva*, F. Druyts*, C. Dorn*, H. Kawamura, "Problems and Future Plan on Material Development of Beryllium in Materials Testing Reactors", JAEA-Conf 2008-011, pp. 55-58, (2008).

7. C. Dorn*, K. Tsuchiya, D. Hashiguchi*, A. Sayer*, H. Kawamura, "Material Selection for Extended Life of the Beryllium Reflectors in the JMTR", JAEA-Conf 2008-011, pp. 59-64, (2008).

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9. K. Kawamata, T. Nakagawa, M. Ohmi, K. Hayashi, A.Shibata, J. Saito, M. Niimi, "Current Status and Future plan of JMTR Hot Laboratory", JAEA-Conf 2008-011, pp. 78-86, (2008).

10. I.L. Tazhibayeva*, T.V. Kulsartov*, E.A. Kenzhin*, O.P. Maksimkin*,T.A. Doronina*, N.S. Silnyagina*, L.G. Turubarova*, K.V. Tsai*, D.A. Zheltov*, V.V. Kashirskiy*, E.V. Chikhray*, V.P. Shestakov*, A.A. Kuykabaeva*, H. Kawamura, K. Tsuchiya, "Structure, Composition and Properties of Lithium Ceramic Li_2TiO_3+5% mole TiO_2 Irradiated in

WWR-K Reactor for Solid Ceramic Blanket of Fusion Reactor", Russian scientific center, "Kurchatov institute", Issues of Nuclear science and equipment, Scientific book, Series Nuclear fusion, pp. 3-11, (2008).

11. I.L. Tazhibayeva*, E.A. Kenzhin*, T.V. Kulsartov*, A.A. Kuykabaeva*, V.P. Shestakov*, E.V. Chikhray*, Sh.Kh. Gizatulin*, O.P. Maksimkin*, I.N. Beckman*, H. Kawamura, K. Tsuchiya, "Tritium Generation in Lithium Ceramics Li_2TiO_3 for Fusion Reactor Blanket", Issues of Nuclear Science and Equipment, Scientific Book, pp. 3-11, (2008).

12. K. Hayashi*, Y. Nagao, T. Nakano*, S. Ichikawa*, K. Tanaka*, T. Takagi*, "Experience of Passing Professional Engineer Exam for Nuclear and Radiation Section", Genshiryoku eye, vol.54, No.10, pp. 44-54, (2008).

13. T. Oku*, R. Kurumada*, Y. Imamura*, M. Ishihara, "Effects of Ion Irradiation on the Hardness Properties of Graphites and C/C Composites by Indentation Tests", Journal of Nuclear Materials, vol.381, pp. 92-97, (2008).

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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	$1L=11=1dm^3=10^3cm^3=10^{-3}m^3$
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	$1\ Oe ≙ (10^3/4π)A\ m^{-1}$

(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	1γ=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	$1\ μ\ =1μm=10^{-6}m$

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