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Annual Report of the Neutron Irradiation and Testing Reactor Center FY 2007 (April 1, 2007-March 31, 2008)

Neutron Irradiation and Testing Reactor Center

Oarai Research and Development Center

March 2009

Japan Atomic Energy Agency

日本原子力研究開発機構

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Annual Report of the Neutron Irradiation and Testing Reactor Center FY 2007 (April 1, 2007 – March 31, 2008)

Neutron Irradiation and Testing Reactor Center

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The Japan Materials Testing Reactor (JMTR), achieving the first criticality in March 1968, has been used to test the durability and integrity of reactor fuels and components, basic nuclear research, production of radioisotopes (RIs), and other purposes. The JMTR, however, was halted in August 2006 after its 165th cycle operation, and is currently undergoing partial renewal of the apparatus and installation of new irradiation equipment, aiming at restarting from 2011. In addition, to cope with strong requests from users to improve the usability of the JMTR, efforts are being made to increase reactor operating efficiency, shorten the turnaround time for obtaining results, and conduct other necessary tasks for the JMTR to recommence reoperation.

The present report summarizes the activities carried out in 2007 for the refurbishment and restart of the JMTR.

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

照射試験炉センターの活動報告（２００７年度）

(2007 年 4 月 1 日～2008 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

（2008 年 12 月 19 日受理）

材料試験炉（JMTR）は、1968 年 3 月に初臨界を達成して以来、原子炉の燃料・材料の耐久性、健全性の試験や基礎研究、ラジオアイソトープ（RI）の製造等に利用されてきた。2006 年 8 月の第 165 サイクルの運転をもって一旦停止し、現在、平成 23 年度からの再稼働に向けて原子炉機器の一部更新及び照射設備の整備を進めている。また、JMTR の再稼働に当たり、利用者からの利用性向上に係る強い要望に応えるため、原子炉稼働率の向上を目指した検討や早く結果が得られるようターンアラウンドタイムの短縮等の検討を進めている。

本報告は、平成 19 年度の JMTR 改修・再稼働に係る活動についてまとめたものである。

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1. Introduction

The Japan Materials Testing Reactor (JMTR, thermal power of 50 MW) is a light water moderated tank-type reactor, that provides one of the world's highest neutron flux of currently operating test reactors. Main specifications are shown in Fig. 1.1.1. Since achieving the first criticality in March 1968, the JMTR has been used in testing the durability and integrity of reactor fuels and materials, basic nuclear research, production of radioisotopes (RIs), and other purposes. Operation of the JMTR was, however, halted in August 2006 following its 165th cycle operation.

The restart of the JMTR has been strongly requested from various users as it is 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 in order to meet a wide variety of irradiation needs. Based on these requests, the Japan Atomic Energy Agency (JAEA) made the official decision to restart the JMTR, and started the refurbishment works in 2007.

Especially, in reinforcing the basis of nuclear power safety, JAEA, with support from the Nuclear and Industrial Safety Agency (NISA) and other related parties, has positioned the JMTR as part of a 'research infrastructure that will bolster the long-term use of light-water reactors in Japan.' JAEA decided to organize optimal administrative structures in securing the internationally competitive technological excellence, convenience, and economical efficiency of the JMTR, and thereby gaining a wide range of users, both domestic and international. Because of this situation JAEA made drastic changes to the administrative framework related to the operation of the JMTR. In 2007 a new propelling organizational framework was launched, centering on the Neutron Irradiation and Testing Reactor Center (hereinafter referred to as "the Center"). The new organization was assigned the primary task of resuming operation of the JMTR in 2011, along with managing the safety of the refurbishment work and responding to various social demands related to the JMTR.

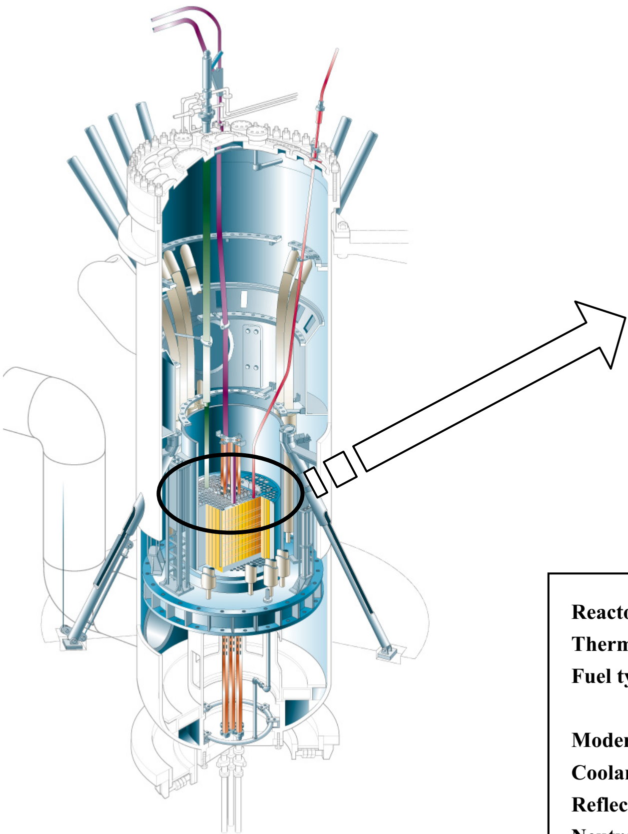
Under this new administrative structure, the Center is currently working at full power toward the establishment of a 'New JMTR' with taking the greatest care to ensure the refurbishment work in a safe and steady manner. The Center is also concerned with increasing the accessibility and usability of the JMTR. The New JMTR will be one of the world's central irradiation test facilities and needs to be capable of meeting demanding requests from users.

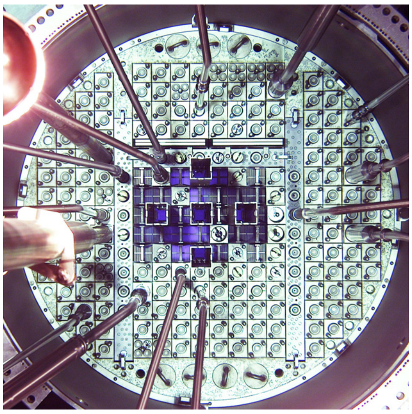
The Center's activities in 2007 with respect to the repair of the JMTR included (1) development of a 4-year (2007-2010) schedule for effective renovations, (2) preliminary work on applying for regulatory approval of regulated equipment and apparatus, and (3) renewal of utility equipment.

Concerning the future operation of the JMTR after the restart, the Center has initiated making channels for promoting co-operation with overseas irradiation testing reactors. Based on the concept that the primary purpose of restarting the JMTR is to provide a test facility which is open to outside users, the Center organized a 'JMTR Steering Committee,' which includes external users as committee members to ensure the transparency of the committee when determining the conditions for performing irradiation tests.

In addition, the Center discussed the means and procedures for receiving requests and proposals concerning the usability and accessibility of the JMTR. Moreover, the Center has initiated the development of irradiation technology that will result in more accurate as well as the world's top level irradiation tests.

New irradiation equipment will be installed using funds from users. Furthermore, to attract new demand the Center has commenced discussions on irradiation equipment related to the production of the medical radioisotope ^{99m}Tc that is used in cancer diagnoses and other purposes.





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)

Reactor pressure vessel

Fig. 1.1.1 Outline of JMTR.

2. Refurbishment of JMTR

2.1 Outline

The reactor equipment to be partially replaced is illustrated in Fig. 2.1.1. The refurbishment schedule (as of December 2007) is outlined in Table 2.1.1. The equipment will be renewed within the present licensing by the regulatory authority; namely, with no changes in design and performance. Details on the equipment to be renewed were evaluated at an 'Expert Committee on the JMTR Refurbishment Plan,' which was set up by JAEA. The meeting of experts confirmed the validity of the basic renewal strategy at sessions that were convened from June to November 2007. The approval procedure to the MEXT (Ministry of Education, Culture, Sports, Science and Technology), which is the regulatory agency responsible for the JMTR, for some of the equipment to be replaced is preparing to apply. The approval procedure will be done in 2008, and the replacement work will be commenced upon after having obtained the necessary approval.

With boiler, pure water production, and other equipment that are not necessary to make the approval procedure, the renewal commenced in 2007, and scheduled to be completed in 2008.

The integrity of the reactor facility was also assessed necessary to establish maintenance plans after reoperation.

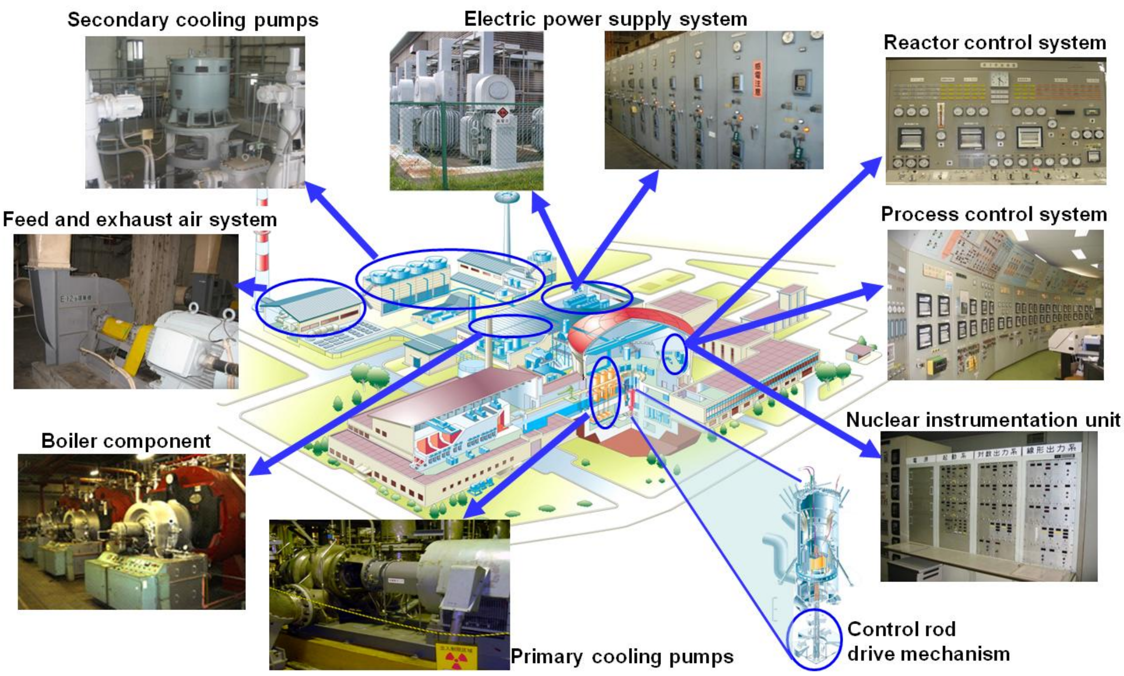


Fig. 2.1.1 Refurbishment of reactor equipments.

Items		FY 2007	2008	2009	2010	2011
Reactor internals	Beryllium flame Gamma shield, etc.					
Instrument and control system	Nuclear instrumentation system Process control system Safety protection system					
Cooling system	Primary cooling system Secondary cooling system, etc.					
Radioactive waste facility	Feed and exhaust air system Drainage system					Restart
Power supply system	High-voltage power supply system Transformer Cable, etc.					
Boiler, etc.	Boiler component Air conditioning system					
Pure water production device	Degassing demineralizer Regular demineralizer					

Table 2.1.1 Schedule of refurbishment work.

2.2 Selection of Renewal Equipments

The equipment to remain in use and that which needs replacing before the restart of the JMTR was selected after having been evaluated on its damage and wear due to aging significance in safety functions, past safety-related maintenance data, and the enhancement of facility operations (e.g., availability of replacement parts). The selection criteria were grouped into two major categories and summarized in the followings.

(1) Safety Criteria

The JMTR is planned to have a 20 years operation after restarting, and therefore replacement priority was given to equipment that had chronologically aged and worn-out. Priority was assigned with special attention to safety concerns. The likelihood of appropriate monitoring being necessary served as an important factor in selecting the equipment to be used after the restart.

(2) Operational Criteria

As the JMTR is planned to operate for a period of 20 years after restarting, appropriate maintenance of the facility will be crucial. Equipment, whose replacement parts are no longer manufactured or likely to be discontinued in the future, was selected, with that list then being used as part of the criteria for renewal.

The equipment and facilities that could be used without renewal (e.g., reactor building, reactor pressure vessel, primary cooling pipes) were assessed as being capable of maintaining their necessary integrity through current maintenance activities and reported as such in the *Periodical Facility Assessment Report on the JMTR Reactor* issued in February 2005. The JMTR will be maintained after the restart according to maintenance plans based on the results of periodical facility assessments. The integrity of the JMTR will also be confirmed through self-imposed regular facility inspections and other checkups.

In selecting the equipment to be renewed this time, the following latest guidelines were referred:

(1) Safety Design Examination Guidelines for Water-Cooled Nuclear Research Reactors (March 2001)
(2) Fire Protection Examination Guidelines for Power Generating Light Water Reactors (September 2002)
(3) Guidelines for Seismic Design Examination of Nuclear Power Reactors (September 2006)

2.3 Renewal Equipments

The equipment to be renewed was re-designed to improve reliability and maintenance capabilities. Major equipment subject to renewal can be summarized as follows:

(1) Primary Cooling System

The equipment and parts that need renewing in the primary cooling system include the primary circulation pump motors and drive members of the main electric and electromagnetic valves. These will be replaced with equivalent products.

(2) Secondary Cooling System

The equipment and parts to be renewed in the secondary cooling system includes the circulating pumps (along with their motors), water pumps (along with their motors), main electric valves, and cooling tower fan motors. These will be also replaced with equivalent products.

(3) UCL (Utility Cooling Loop) System

The equipment and parts to be renewed in the UCL system include the circulation pumps (along with their motors), water pumps (along with their motors), main electric valves, and cooling tower fan motors. These will be also replaced with equivalent products.

(4) Instrumentation and Control System

The equipment to be renewed in the instrumentation and control system include the reactor control panel (complete renewal), process instruments (complete renewal), nuclear instruments (complete renewal), and part of the control rod drive mechanism. The instrumentation equipment was classified by type (display, operation switch, etc.). The equipments will be upgraded to improve operational efficiency and visibility in creating better man-machine interface.

The equipment to be renewed was not subjected to any major changes in design or performance. Renewal of the boiler, pure water production, and other related equipment that didn’t need the approval procedure commenced in 2007 and will be completed in 2008. With the boiler equipment, replacement of the refrigerator of the air conditioning system of the reactor building was completed in 2007.

Updating the other equipment that required the approval procedure will be carried out in 2008, with refurbishment work to be commenced after the necessary approval has been obtained.

2.4 Integrity Inspection for Equipments

The JMTR is planned to be operation for 20 years after restarting in 2011. In ensuring the long-term safe use of the reactor equipment, basic data will need to be obtained during the refurbishment period to then be used in establish maintenance plans after reoperation. In 2007, therefore, integrity inspections of the reactor facilities were carried out. The major inspections that took place encompassed the following:

- insulation resistance of the diesel engine generator (power supply unit)
- the integrity of the JMTR reactor building
- the integrity of the reactor pressure vessel and heat exchangers (primary cooling system), and
- the secondary cooling tower and inner lining of the secondary pipes (secondary cooling system).

The results of these inspections will be used in the planning of the preventive maintenance and management plans that will be implemented in the reoperation of the JMTR.

2.5 Installation of Irradiation Facilities

To increase the demand for use of the JMTR, the feasibility of producing the medical radioisotope ^{99m}Tc, which is used in cancer diagnoses and for other purposes, was examined. Evaluation of the possibility of modifying part of the current hydraulic rabbit irradiation equipment also commenced. A schematic diagram illustrating the possible modification is provided in Fig. 2.5.1.

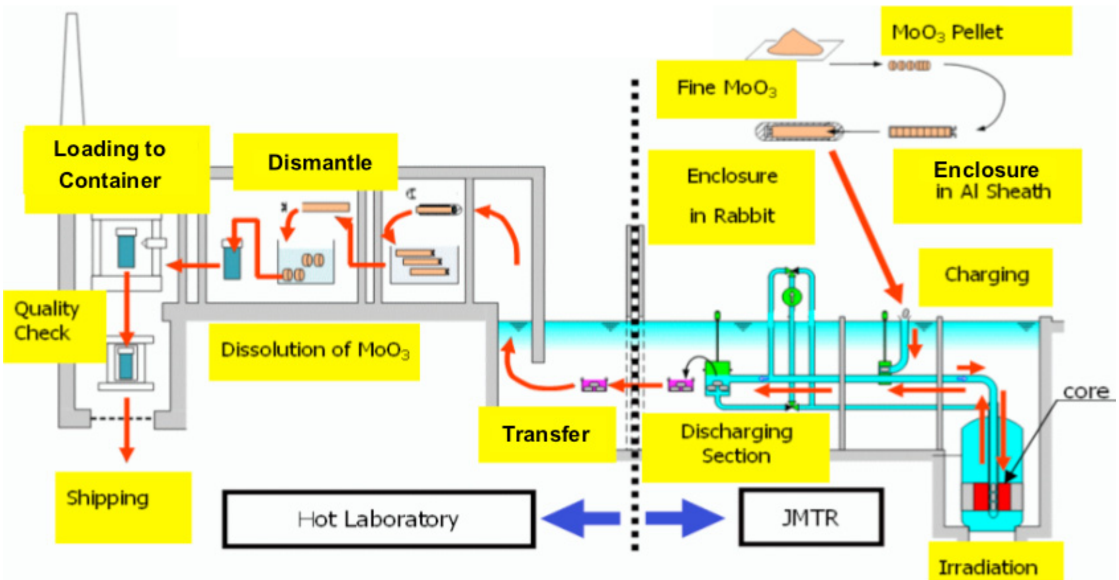


Fig. 2.5.1 Conceptual process diagram of the ^{99}Mo production procedure for the hydraulic rabbit irradiation facility.

3. Utilization promotion of JMTR

In achieving the attractive irradiation reactor to use for users after reoperation of the JMTR, following improvements with respect to usability and accessibility are being carried out:

-Achieve reactor operation rate of 50% to 70%,
-Shortened the turnaround time for obtaining results,
-Competitive irradiation cost compared with other testing reactors around the world,
-Simplify the procedures and improve the technical support system for enhanced accessibility and increased availability of the JMTR
-Strengthened management of data in securing confidential information

3.1 Inauguration of the Neutron Irradiation and Testing Reactor Center

In the past, operation of the JMTR, including the management of use for external users and the management of the facility itself, was solely controlled by the former Material Testing Reactor Department, which led to the availability of use-related technical support being rather poor. To cope with this issue, as well as to make more user-friendly and user-oriented the JMTR operation programs that can propose attractive irradiation tests available and develop as an international irradiation center, the Neutron Irradiation and Testing Reactor Center (consisting of a Project Coordination Section, an Utilization Promotion Section, and an Irradiation Engineering Section) was set up on April 1, 2007 in the Oarai Research and Development Center. To efficiently update, maintain, and manage the JMTR facility, the Material Testing Reactor Department that used to govern the JMTR operations was dismantled and reorganized as the Department of the JMTR Operation (which included the five sections of Administration Section, a JMTR Reactor Engineering Section, a JMTR Refurbishment Section, a JMTR Irradiation Facility Establishment Section, and a JMTR Hot Laboratory Section) on August 1, 2007. The new department was added, forming part of the Center.

Under the supervision of the Director of the Center, the institutional framework was set to enable the facility management, including the refurbishment, operation, and maintenance of the JMTR, to be undertaken by the Department of JMTR Operation, while use of the facility would be managed independently through the concerted cooperation of the Project Coordination Section, an Utilization Promotion Section, and an Irradiation Engineering Section. This institutional restructuring is expected to contribute to the promotion of use of the JMTR irradiation facility and the improvement of technical support.

3.2 Establishment of the JMTR Steering Committee

On February 4, 2008, the JMTR steering Committee was formed to conduct the user-friendly irradiation utilization of the JMTR with reflecting users opinions/comments directly, so-called transparent management. (see Fig. 3.2.1) The first meeting of the Committee was held on March 25, 2008 to discuss the achievement of 50%～70% of reactor operation rate in a year, shortening the turnaround time, and achievement of the attractive irradiation cost in comparison with other research reactors in the world. The activities of the JMTR steering committee can be summarized as follows:

3.2.1 Improvement of Reactor Operation rate

Until now, the reactor operation rate of the JMTR was about 50 % (annual reactor operation:180 days). To increase the reactor operation rate at about 60% (annual reactor operation:210 days), discussions were started taking account of the following:

- the former maintenance program should be changed into the preventive maintenance type to reduce the reactor shutdown possibility caused by trouble and/or failure of equipments,
- the reactor operation scheme should be optimized.

3.2.2 Shorten Turnaround Time

In the irradiation use of the JMTR, the user makes application first, and then design and manufacture of the capsule are carried out. After that, the irradiations and post-irradiation examinations are carried out. Finally, the user gets the measured data. For this utilization process, discussions were started to shorten the turn-around time which is the period from application to get measured data. In particular, discussions are focused on the shortening period of the design and manufacture of the capsule from maximum of 1.5 years to a few months.

3.2.3 Achievement of Attractive Irradiation Expenses

The Center is discussing a market-competitive pricing system for use of the JMTR, while also exploring ways of cutting operating and maintenance costs. The forthcoming pricing system aims to reduce the research & development costs of nuclear research institutes, cope with a national request for development and accumulation of domestic atomic technologies, and ensure the globally attractive irradiation fees.

To acquire more information for establishing the JMTR facility fee system, the Center surveyed the use tariff systems for national and international irradiation facility to know in detail on current market price levels. As reference for use in developing the JMTR facility fee system, the Center sent also personnel to the High-Flux Advanced Neutron Application Research Reactor (HANARO) Center in South Korea to obtain related information. In addition, the Center obtained similar information from researchers visiting nuclear agencies and testing reactor facilities in Europe and South East Asia.

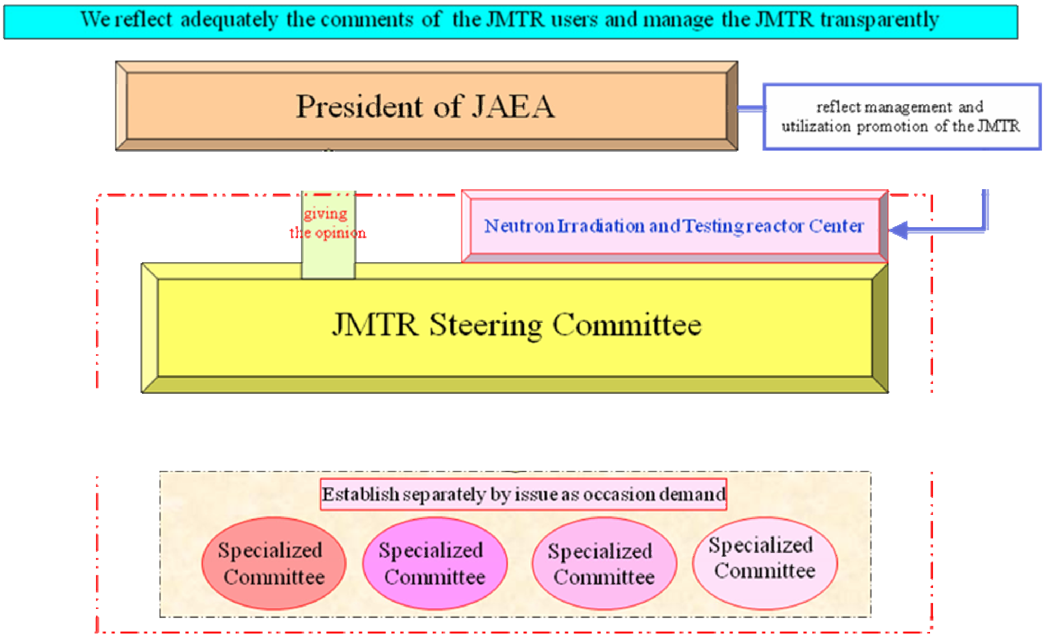


Fig 3.2.1 Establishment of JMTR Steering Committee

4. Development of Irradiation Technologies

4.1 Preparation of New Irradiation Engineering Building

The neutron irradiation and testing reactor center is developing new irradiation test methods to encourage sophisticated use of the JMTR irradiation facility and thus provides irradiation data of high technical value. The development of capsules for material irradiation tests requires a significant amount of space for assembling the capsules and performing tests, inspections, and analysis of irradiation samples. For that purpose, the RI Application Development Building will be planned to use in carrying out irradiation technology development. In 2007 the electricity and water were supplied, and air conditioning equipment and a sewage system were installed in the building. After renovation of the building experimental apparatuses necessary for developing new irradiation techniques will planned to install.

4.2 Irradiation Technology for LWR Fuel and Material

4.2.1 Development of Fuel Irradiation Testing Apparatus

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

The testing facility will consist of shroud irradiation equipment, capsule control equipment, and He-3 power control equipment. As some parts of the design details, the system design and the instrumentation design were carried out.

The shroud irradiation equipment consists of reactor piping, cooling system, capsule exchanger, and an instrumentation and control system. The capsule control equipment supplies water simulating a light-water reactor environment. The He-3 power control equipment controls the power of the testing fuel by changing the He-3 pressure.

In the system design, two parallel wastewater-treatment-lines are considered to conduct continuously the fuel failure test by changing lines. At the same time, the wastewater is designed to be reutilized through being circulated (purified) to reduce the amount of discharged water. The system design of the fuel irradiation testing apparatus is illustrated in Fig. 4.2.1.

With the instrumentation design the specifications and detailed construction of components were concluded. An investigation was made on the material to be used for the tritium trap of the He-3 power control equipment while taking note of the possible utilization or recycling of tritium. These achievements are some of the results in a project funded by Nuclear and Industrial safety Agency (NISA) in 2007.

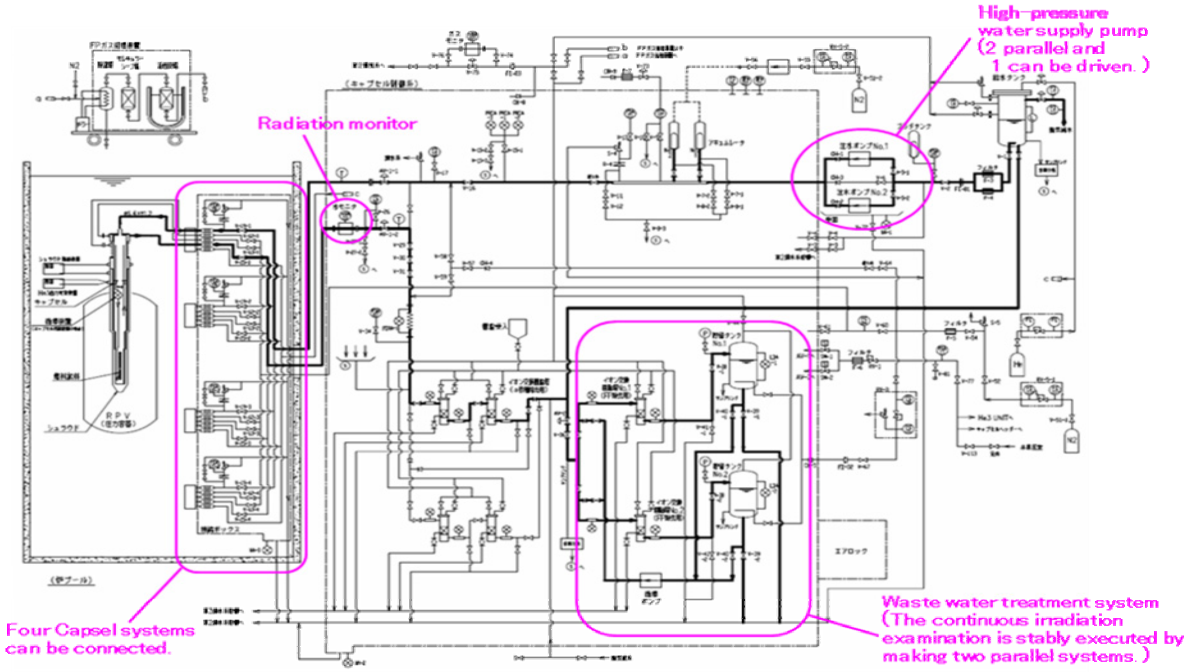


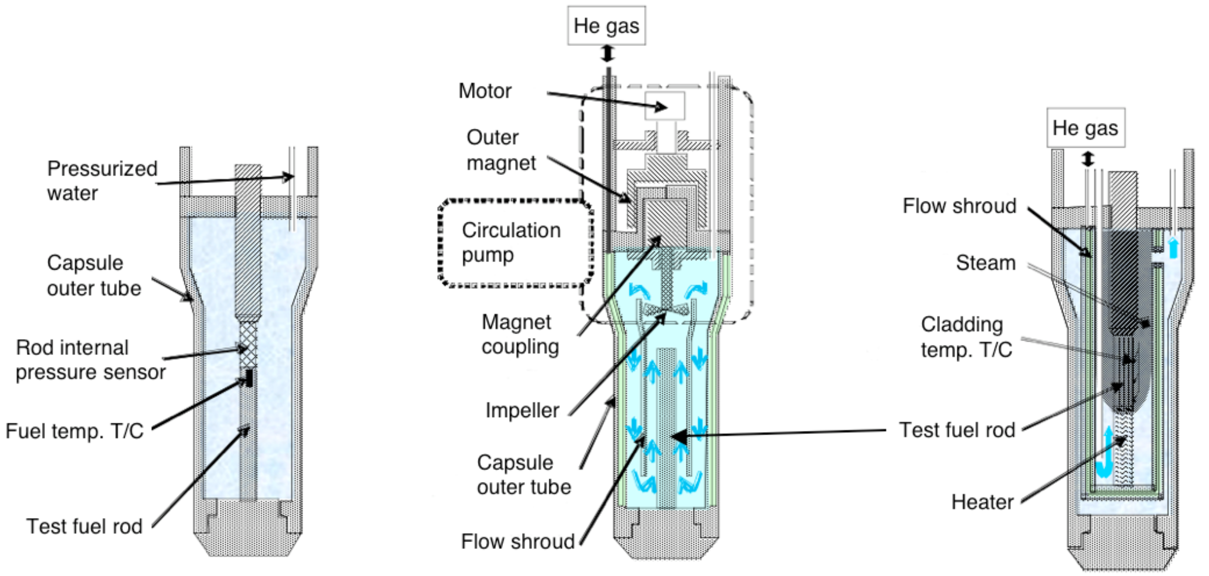
Fig. 4.2.1 System diagram of fuel irradiation testing apparatus.

4.2.2 Transient Test Capsule for Fuel

Development of capsules for fuel transient tests was carried out as design activities. The capsule designs were completed for power transition tests of PWR and BWR fuels. Here, designed capsules are the following three types; a natural convection type used commonly in power ramping tests, forced convection type and dry-out capsule type. These are schematically illustrated in Fig. 4.2.2.

Basic structure for measurements of fuel temperature, rod internal pressure and fuel cladding expansion was studied for the natural convection capsule. For the forced convection capsule, a circulation pump by magnet coupling was studied. For the dry-out capsule, structure to maintain a dry out condition was studied.

These achievements are some of the results in a project funded by Nuclear and Industrial Safety Agency (NISA) in 2007.



a) Natural convection capsule b) Forced convection capsule c) Dry-out capsule

Fig. 4.2.2 Schematic drawing of transient test capsule for fuel.

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 developing. The facility consists of a water environment control system, weight-loading control unit and capsules.

The water environment control system feeds quality-controlled, high-temperature and high-pressure water to the capsule to simulate the in-core environment, such as the temperature, pressure, and water quality of the light-water power reactor. The system also purifies and circulates water from the capsules.

The design of the water environment control system in the BWR material irradiation facility simulating the BWR environment and the BWR/PWR material irradiation facility simulating the broad water environment was carried out. The components of dissolved oxygen / hydrogen concentrations and zinc injection were designed for the BWR material irradiation facility to simulate the BWR condition. The system also provides the temperature control, flow rate and pressure control. Diagram of the system is shown in Fig. 4.2.3.

Additionally, the boron and lithium injecting components were designed for the BWR/PWR material irradiation facility. The water environment control system was designed to selectively remove boron and lithium from the circulating water.

These achievements are some of the results in a project funded by Nuclear and Industrial safety Agency (NISA) in 2007.

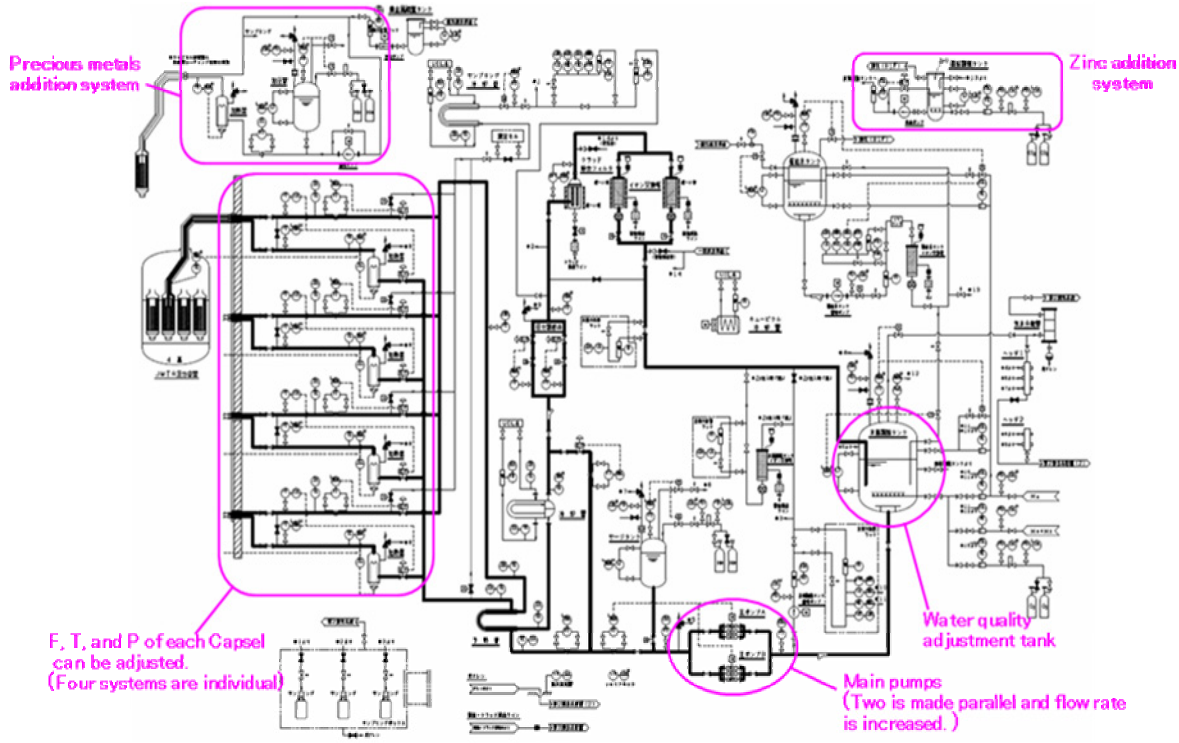


Fig. 4.2.3 Diagram of material irradiation facilities.

4.2.4 In-pile SCC Growth Test Unit

Austenitic stainless steel, which is used in the internals of a light-water reactor core, is known to undergo irradiation-assisted stress corrosion cracking when exposed to neutron irradiation. To investigate this behavior, crack growth and initiation tests were carried out using the JMTR from 2000 to 2007. The results suggest that large-size irradiation test specimens [0.5T-CT (B = 12.7 mm)] would be required in accurate of fracture mechanic analysis for the effective range of the stress intensity factor (K value) within a low neutron fluence range (for low yield-stress materials).

Consequently, in 2007, to develop the crack growth test unit, specific attention was paid to the structure of the weight-loading mechanism, measurement method for crack growth, and detection method for specimen breakages when irradiating large-size. The examination resulted in a better weight-loading mechanism being identified, in which the specimen was placed in the reverse direction of the previously used direction and the specimen ligament was placed on the opposite side of the unit (Fig. 4.2.4). This new mechanism was subsequently adopted for use. The new structure provides a shorter distance between the point of action and point of support; therefore a shorter unit length can be attained for a higher leverage ratio, thereby enabling the unit to completely fit inside a capsule. Structural analysis of the unit revealed that the equivalent stress on the stainless (SUS 630) member of the unit was within the elastic region (maximum: about 700 MPa), and that the maximal displacement was around 2.6 mm, thus preventing the unit from colliding with the lever member placed on the opposite side. These results have raised the prospect that adoption of the structure will achieve the target weight load on a test piece (approx. 7.6 kN).

These achievements are some of the results in a project funded by Nuclear and Industrial safety Agency (NISA) in 2007.

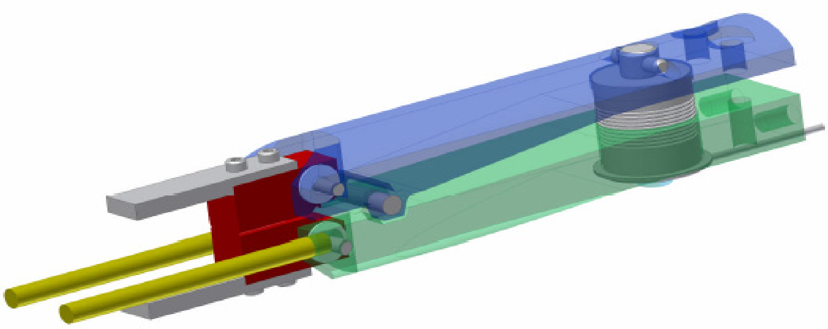


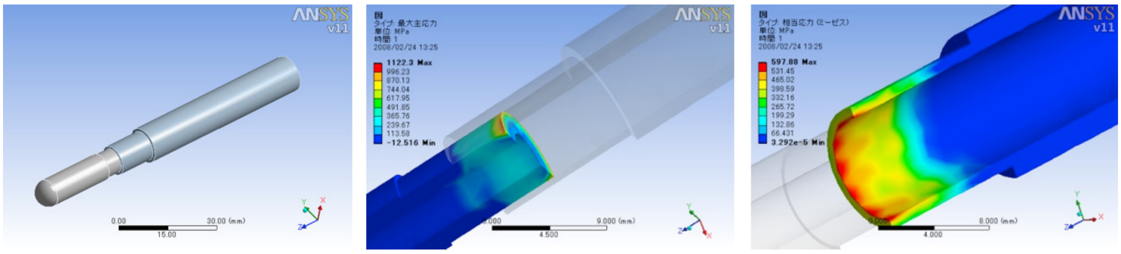
Fig. 4.2.4 Schematic illustration of the newly proposed weight-loading unit structure.

4.2.5 ECP Sensor

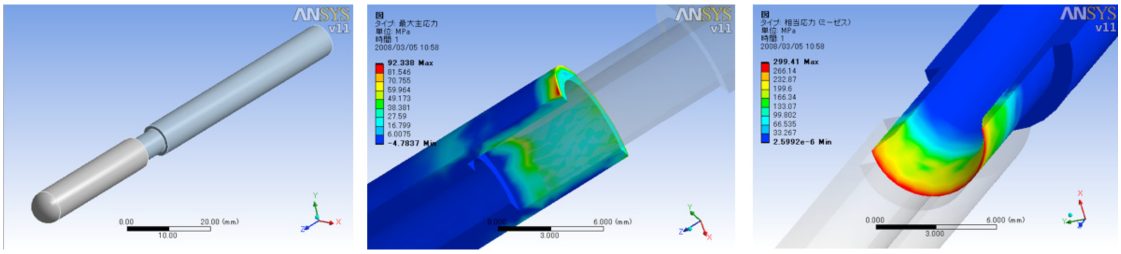
The water chemistry in a light-water reactor has been found to considerably differentiate from that of the water supplied to the reactor due to chemical species being generated by the decomposition of water caused by neutron and gamma irradiations. To measure that water chemistry in a light-water reactor, the Electrochemical Corrosion Potential (ECP), a widely used qualitative index, needs to be measured in-situ under in-core irradiation conditions. However, conventional ECP sensors have not been practically applied in this purpose because of their fragility; they are often damaged under high neutron-flux conditions. This underscored the need to develop ECP sensors that are more durable up to high neutron fluence.

Critical damage to conventional ECP sensors occurs when a crack is formed in the vicinity of the joint between the zirconia-based sensor and the metal sleeve, and results in sensor malfunctioning. The crack may be partly caused by residual stress generated in the connecting part of the zirconia and the metal. To reduce the effect of that residual stress, therefore, structure analysis was performed on the joint section to optimize the properties, size, and shape of the materials. In analyzing the joint structure a parameter survey was carried out on its dimensions and shape using the finite element method in determining the dimensions and shape that would achieve the largest residual stress reduction when compared with conventional sensors. In selecting the sleeve material, use of SUS430 and platinum, instead of 42 alloy, was found to present the likelihood of reducing the residual stress. Typical examples of conventional and improved electrochemical corrosion potential sensors are shown in Fig. 4.2.5.

These achievements are some of the results in a project funded by Nuclear and Industrial safety Agency (NISA) in 2007.



(a) Conventional electrochemical corrosion potential sensor: (left to right) general view of the sensor, residual stress on the zirconia sensor, and residual stress on the sleeve.



(b) Improved electrochemical corrosion potential sensor: (left to right) general view of the sensor, residual stress on the zirconia sensor, and residual stress on the sleeve.

Fig. 4.2.5 Results of analysis of residual stress.

4.3 Irradiation Technology for Advanced Instrumentation

4.3.1 Multi-paired T/C for High Temperature

Irradiation tests require various irradiation temperature conditions that simulate the actual environments (e.g., fuel type, materials, irradiation atmosphere, and irradiation temperature), and the research was accordingly conducted on the development of thermocouples to measure the irradiation temperatures with precision. Thermocouples that were previously used in irradiation tests were mainly of the chromel-alumel (K)-type. The highest applicable temperature limit of the k-type thermocouple, which varies with the diameter of the wire, is 800°C for ordinary measurement conditions and 1000 to 1200°C for short-time measurement conditions. Consequently, the JMTR has delivered excellent measurement records with a thermal neutron fluence of up to 5.0×10^{25} n/m^2. However, when used at irradiation temperatures exceeding 1000°C, K-type thermocouples become short-lived, thus indicating that conventional K-type thermocouples are not suitable for use in irradiation tests of fuel materials for next-generation reactors, high-temperature gas-cooled reactors, and nuclear fusion reactors.

For these reasons, development of nicrosil-nisil (N-type) thermocouples, which have excellent heat resistance to irradiation temperatures above 1000°C, possess the appropriate thermoelectric properties, and involve little nuclear transmutation was focused. In 2007, trial fabrication of N-type thermocouples, and conducted tests were carried out. These multi-paired thermocouples, which have a maximum of seven hot junctions per small-diameter sheath, are intended for use in measuring the temperature gradient along the long axis of light-water reactor fuel.

Figure 4.3.1 shows the results of radiographic analysis of the hot junction positions along the axis to determine the manufacturing errors of the trial products. The results revealed that three trial multi-pair thermocouple products had hot junctions within 1 mm of the predetermined axial positions. The trial thermocouple products yielded measurement data within a 1-percent error, which fell within the predetermined allowable range. Future plans include out-pile thermal cycling tests and durability tests on the trial thermocouple products in verifying their applicability in actual irradiation test conditions.

Positions of hot junctions		A	B	C
Distance between hot junctions (designed value, mm)		50.0	30.0	30.0
N type Multi-paired T/C (measured value,mm)	No.1	49.0	30.0	30.0
	No.2	49.0	30.5	30.0
	No.3	49.0	29.5	29.5

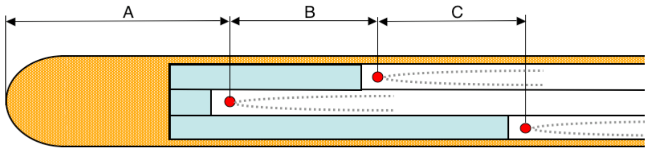
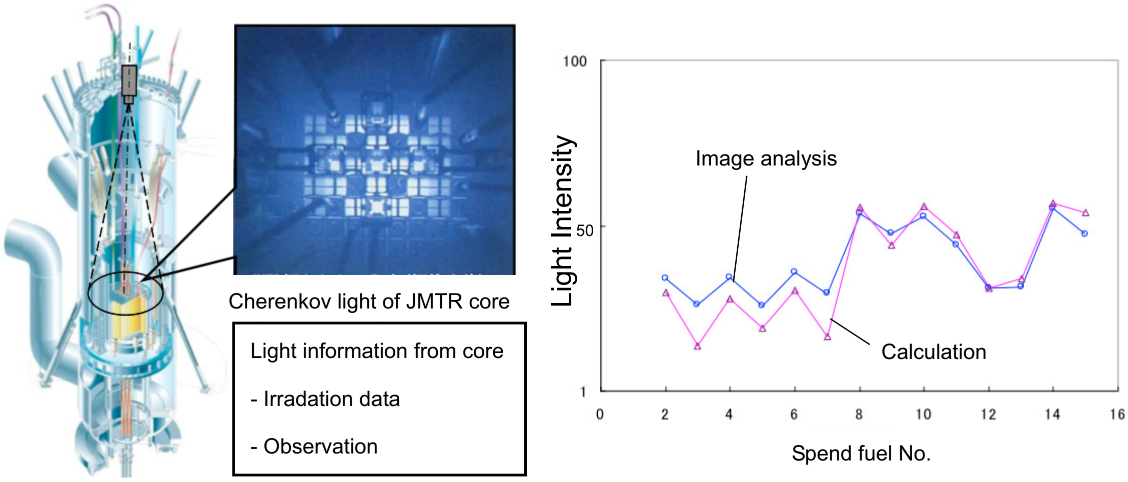


Fig. 4.3.1. Results of position measurement of trial N-type thermocouple hot junctions.

4.3.2 Development of In Situ Monitoring System

To develop an advanced core management and measurement system applicable to the restart of the JMTR, in-core monitoring system is developing. It will monitor the in-core conditions in real time and retrieve nuclear and thermal information as optical data. The intention is to accurately detect any subtle deviations in the core conditions that were not noticeable using the conventional measurement systems. A schematic drawing of the in-core optical information retrieval system is given in Fig. 4.3.2.

As part of the preliminary examination of this system attention was paid to Cherenkov radiation as a possible ways of enabling real-time optical data transmission during nuclear operation, with analysis being carried out on emissions from spent fuels. Measurement of Cherenkov light was performed by analyzing video camera images of the spent fuels stored in the spent fuel pool rack of the JMTR canal. To verify the validity of the measurement results, Cherenkov emission rates were estimated for the spent fuels based on gamma-ray intensity distributions obtained computer codes for calculating radiation sources (ORIGEN-JR). The results of comparing the data derived from image analysis and calculations are also shown in Fig. 4.3.2. The results indicate a strong correlation between the image analysis data and the emission intensity estimation data, thus offering the realistic prospect of practical application of this technique.



(a) Schematic drawing of in-core optical information retrieval system

(b) Comparative analysis of spent fuel optical data

Fig. 4.3.2 Concept of in-core optical information retrieval system and preliminary analysis results.

4.3.3 In-situ Measurement of Water Chemistry by Light Monitoring System

Water quality control of a light-water reactor is crucial in elucidating the SCC mechanism and taking countermeasures against it. It needs to be based on accurate measurement of the concentrations of oxidative chemical substances such as dissolved oxygen and hydrogen peroxide that are considered responsible for the corrosion of in-core materials. With presently used water quality control reactor water is sampled and the dissolved oxygen and hydrogen peroxide were measured on out-of-pile and the results then used in estimating the corrosivity. However, water samples collected from high-temperature, high-pressure and high-irradiation conditions exhibit rapid changes in chemical composition, making it therefore difficult to precisely measure the levels of chemical compounds affecting the corrosion of the core internals. For these reasons the measurement apparatus that can more accurately determine the concentrations of the chemical compounds generated in that kind of environment is developing.

The apparatus is designed to provide in-situ measurement data on in-core water through use of optical fibers. The measurement takes advantage of the absorption properties of chemical substances and the photoluminescence properties of chemical reactions in providing ample information within a short timeframe. A prototype apparatus was made by combining an optical fiber spectrometer and chemical sensors to examine the basic performance in quantitative response to hydrogen peroxide concentrations. An overview of the prototype apparatus is shown in Fig. 4.3.3. The results indicated an excellent response to hydrogen peroxide concentrations of not less than 20 ppm, suggesting that it could identify the chemical compounds.

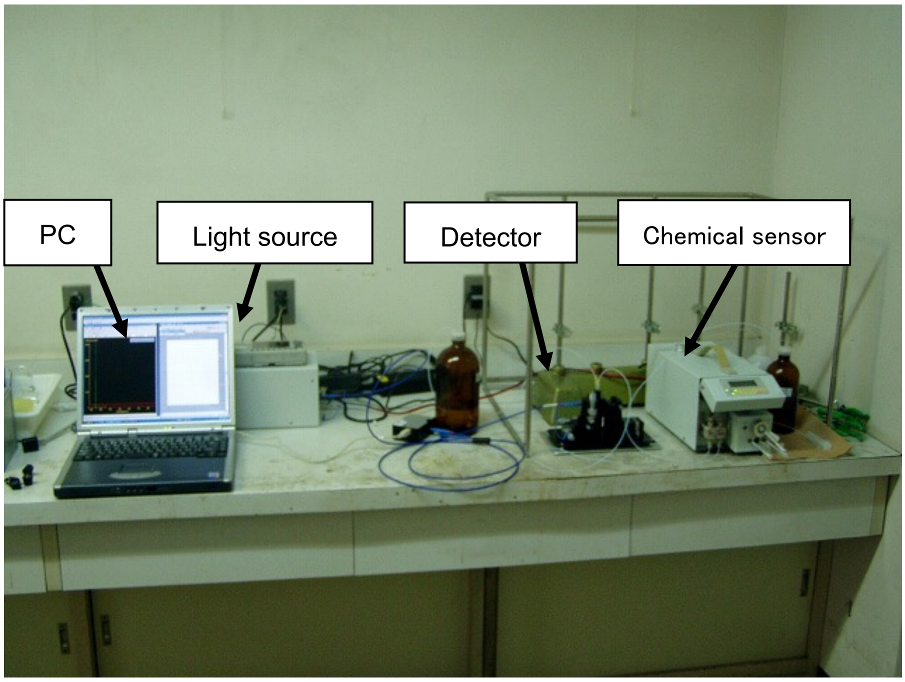


Fig. 4.3.3 Overview of trial reactor water analysis apparatus version.

4.4 Irradiation Technology for Industry Use

4.4.1 Conceptual Development of Silicon Irradiation Equipment

Silicon semiconductors are finding their way into a wide variety of devices in the world with increasing demands for six- and eight-inch diameter silicon semiconductor slices (wafers). Silicon semiconductors, which are used in hybrid cars, fuel cell vehicles equipped with control inverter devices, inverter-controlled high-speed transportation mechanisms, etc., are making a significant contribution to developments in power electronics. The industry sector, therefore, is facing a greater need for silicon semiconductor production. Furthermore, the Center has carried out conceptual development of silicon irradiation equipment applicable to the JMTR under this situation.

From viewpoints of thermal flux and so on, a possible place for setting up silicon irradiation equipment was the 4 × 4 hole (J, K, L, M- 1, 2, 3, 4) region, which is north of the JMTR core, and hence feasibility of installing silicon irradiation equipment in this region was investigated.

A schematic drawing of the silicon irradiation equipment is given in Fig. 4.4.1. Silicon material can be loaded into the core from the vicinity of the reactor water pool, and it will then be irradiated with rotation itself. Then, the irradiated silicon material can be automatically transferred to an exclusive storage place to cool. As a result of the conceptual design, the favorable prospect was obtained that irradiation could be carried out on up to eight-inch diameter silicon wafers.

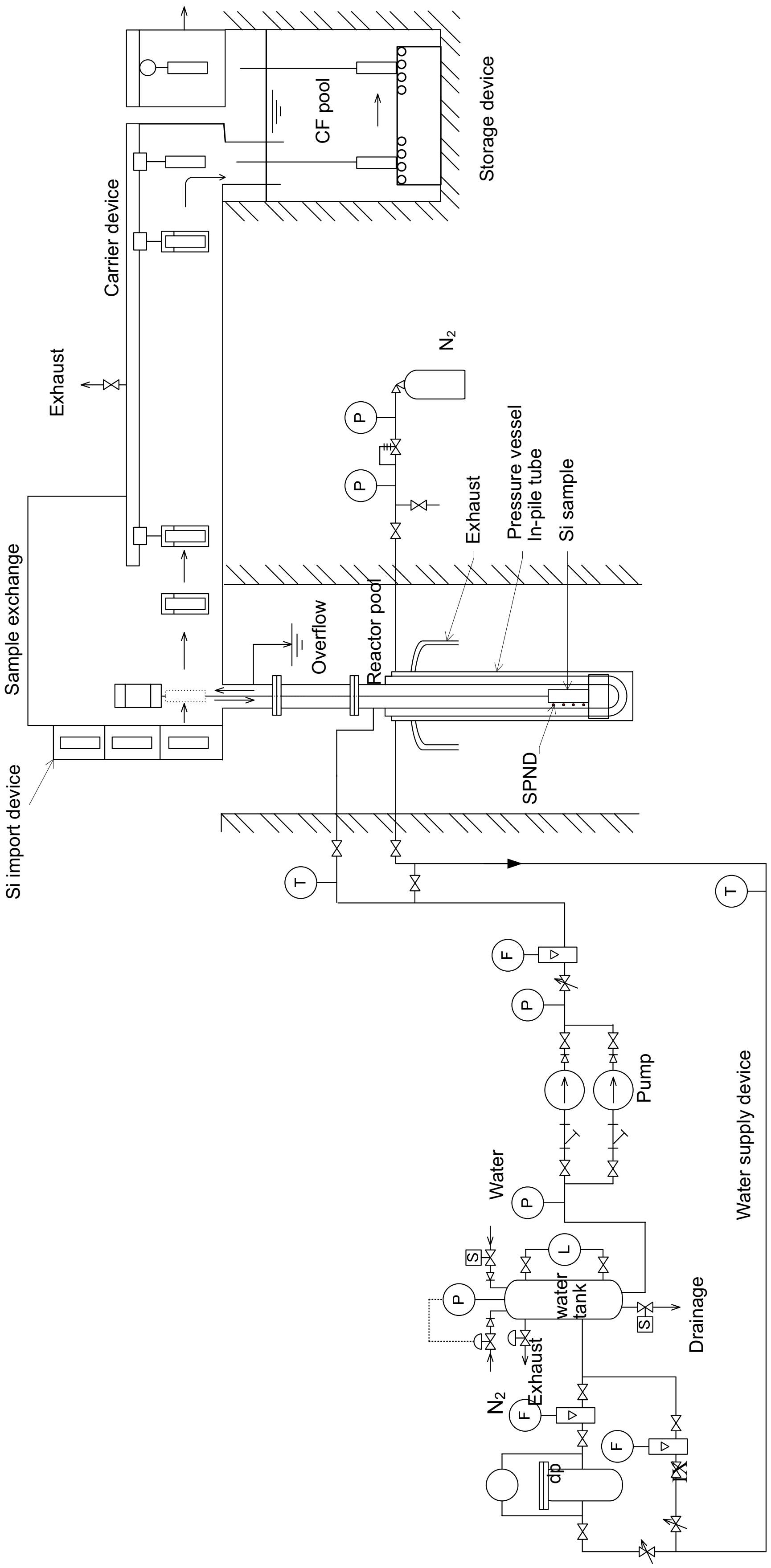


Fig. 4.4.1　Conceptual design of silicon semiconductor production apparatus.

4.4.2 ^{99}Mo Production Facility using Hydraulic Rabbit Irradiation Facility

As part of the effective use of the JMTR after restarting the Center plans to employ the hydraulic rabbit irradiation facility to produce molybdenum-99 (^{99}Mo; half life: 66.7 hours), the parent nuclide of technetium-99m (^{99m}Tc; half life: 6 hours) that is used in diagnostic nuclear medical procedures.

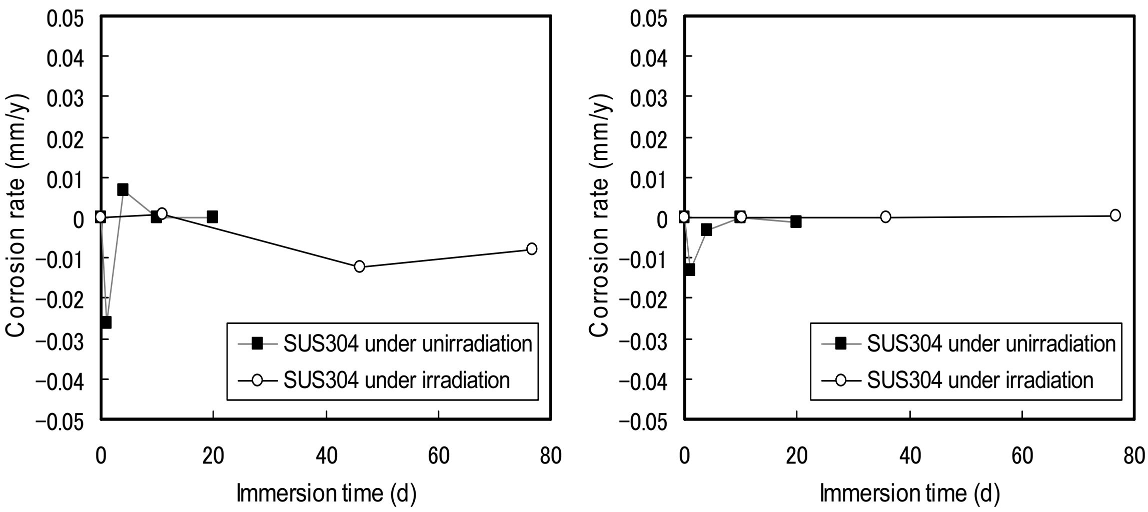
In 2007 the Center developed a conceptual framework for production using the hydraulic rabbit irradiation facility based on the (n, γ) method, that can produce approximately 20% of the overall amount of ^{99}Mo (88.8 TBq/week; 2400 Ci/week) imported and used domestically.

The process diagram for ^{99}Mo production is already given in Fig. 2.5.1. Pelletized molybdenum trioxide (MoO_3) is sealed in a rabbit holder, irradiated for appropriate time, withdrawn, and then transferred via the water canal to the hot laboratory, where ^{99}Mo is extracted from the cells and then shipped to medical institutions or other facilities. To produce approximately 20% of total domestic demand, another hydraulic rabbit irradiation facility will need to be installed. In consideration of the thermal neutron flux, the number of irradiation specimens, and other factors, the new reactor tube will need to be placed in the M-9 irradiation hole. Previously, the hydraulic rabbit irradiation tubes had been installed in the M-9 irradiation hole. Moreover, since its core lattice dimensions are compatible with a 3-inch loop, it can install longer reactor piping, allowing a maximum of five, rather than three, rabbits to be simultaneously loaded. This will contribute to increased ^{99}Mo production capacity. If 6-day rabbit irradiation is assumed the standard 30-day cycle operation of the JMTR can provide four lots of irradiation. A maximum of six loaded rabbits will be available with two hydraulic rabbit irradiation facilities. If 2.5 days are needed between irradiation termination and shipment, it is estimated that 18.5 TBq/week (500 Ci/week) ^{99}Mo can be produced. The Center is further contemplating the improvements of shipment capacity to approximately 37 TBq/week (1,000 Ci/week) ^{99}Mo by increasing the MoO_3 density and number of loaded rabbits from 3 to 5 with the new hydraulic rabbit irradiation facility. A detailed design specifying these issues will be planned in next year.

4.4.3 ^{99}Mo Production Technology by Mo Solution Irradiation Method

The solution irradiation method has been proposed as a new approach to produce ^{99}Mo, the parent nuclide of ^{99m}Tc that is used in diagnostic nuclear medical procedures. This new approach employing the (n,γ) reaction, in which molybdenum solution is neutron irradiated in the reactor core in the presence of poly zirconium chloride (PZC) molybdenum adsorbent, provides ^{99}Mo more efficiently and at a lower cost than with conventional procedures. However, to practically apply this approach the properties of the irradiation target, molybdate salt solution, will need to be precisely evaluated.

Two types of molybdate salt solution samples (ammonium molybdate solution and potassium molybdate solution) were chosen as candidate irradiation targets. The samples were subjected to gamma irradiation, and analysis performed on the compatibility of the solutions and the structure materials, as well as the chemical stability, circulation properties, radiation decomposition, and gamma-ray heat generation of the solutions. In evaluating the compatibility of the selected solutions and the structure materials test specimens were immersed in the solutions, and corrosion rates calculated using the duration of immersion and the weight change of the test specimens. The test specimens were made of stainless steel (SUS304), which has been used in the JMTR. The relationship between the duration of the test specimen immersion and the corrosion rate are illustrated in Fig. 4.4.3. The immersion lasted a maximum of about 77 days, and gamma rays were irradiated for about 61 days (intensity: 2.3×10^5 Gy/d). From both results, it can be said that the corrosion rate is small, and that the irradiated solutions do not tend to provide larger corrosion rates than the non-irradiated solutions. The results raised the prospect that stainless steel could be used for the capsules and pipes. Moreover, the results also revealed the followings: the selected solutions were chemically stable under irradiation; circulation of the irradiated solutions was not hindered; the hydrogen content of the gas generated by irradiation decomposition of the selected solutions was higher than with pure water; and the selected solutions had a gamma-ray heat generation rate similar to pure water.



(a) Ammonium molybdate solution (b) Potassium molybdate solution

Fig. 4.4.3 Relationship between duration of immersion of SUS 304 test piece and corrosion rate.

4.5 Irradiation Technology for Beryllium Reflector

4.5.1 Lifetime Extension

Beryllium (Be) metal is used in the reactor components of the materials irradiation test reactor of the JMTR with its low neutron absorption cross section and large scattering cross section. Be metal components, however, need to be replaced at regular intervals due to the change in mechanical strength resulting from neutron-induced nuclear reactions that produce He and irradiation-induced bending or swelling. Development of Be components which is free of regular replacement can help increase the operating performance of the JMTR and reduce the amount of radioactive waste, and hence the enhancing the durability of Be metal components is studying.

Be test specimens, two grades of Be metal (S-200F and S-65C) of differing beryllium oxide (BeO) impurity content, were prepared by treating in a variety of conditions (including those used in the recent frame fabrication method). The specimens were then subjected to preliminary irradiation study at the JMTR to examine the irradiation effects.

To carry out the study the newly developed a capsule-dismounting device that would prevent the release of neutron-generated tritium from Be into the hot cells and a remote-control high-accuracy measurement apparatus formed through combining a laser and a high-precision auto-staging device (Fig. 4.5.1). As a result of the preliminary study, a significant difference was found in the tensile strength of the irradiated Be specimens that was the result of differences in the BeO impurity content and treatment conditions. The remote-control high-accuracy measurements also revealed that S-65C Be specimens irradiated in neutron fluences of up to 1 $\times 10^{24}$ /m^2 (E > 1 MeV) showed no signs of bending under the irradiation conditions. The results of the preliminary study also suggested the possibility of enhancing the durability of the Be neutron reflectors.

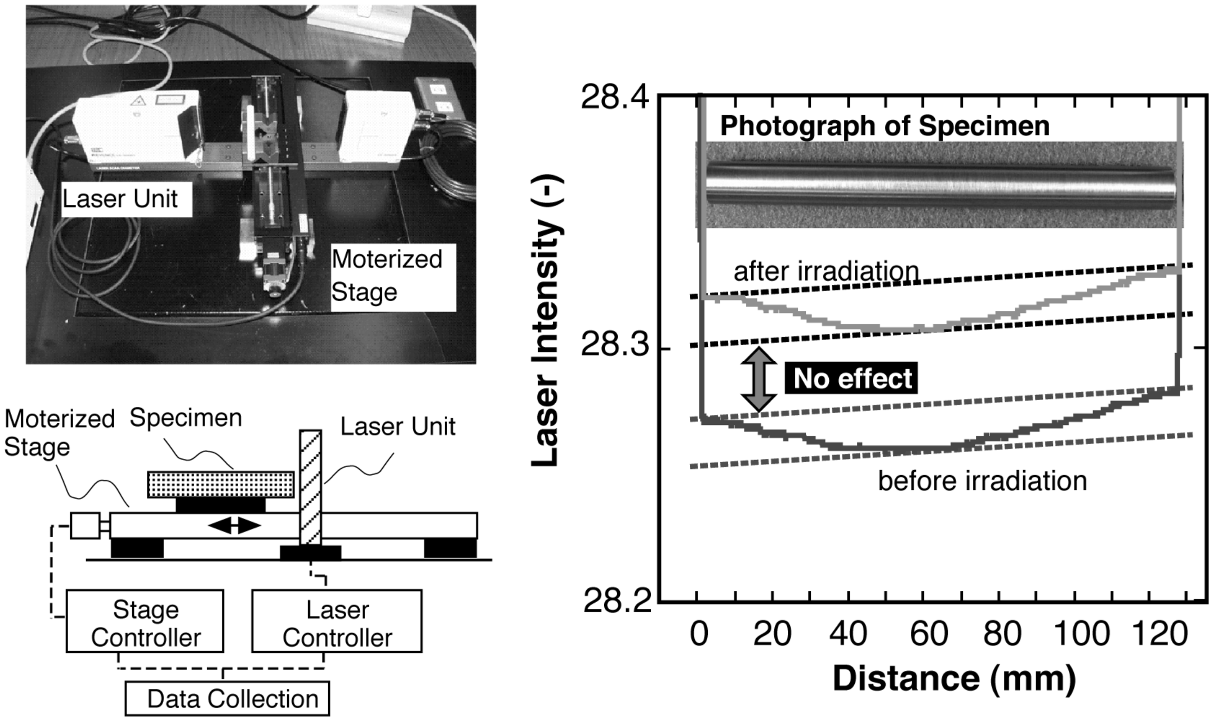


Fig. 4.5.1 Remote-control high-accuracy dimension measurement apparatus.

4.5.2 Beryllium Recycling Technology

Be component waste causes significant disposal problems in most countries where research reactors are operated and has to be stored in the nuclear facility awaiting disposal due to the tritium gas generated by neutron irradiation, strict international control as an essential component of nuclear weapons, designated and regulated as harmful to human health.

At present, a total of approximately 2 to 3 tons of irradiated Be waste is being stored in the JMTR canal. In the USA neutron-irradiated Be waste was once disposed in the desert, then it created a serious environmental issue because long half-life ^{14}C generated through irradiation from the buried Be waste entered and contaminated the underground water system.

Recycling of 'used' Be materials, thus, has proved to be an important task in tackling the effective utilization of material resources. Researches in laboratory scale have been conducted on recycling Be waste, and the recycling methods developed to date have involved the thermal decomposition of Be and gaseous chlorine reaction products at 1500°C in attempting to separate and recover Be metal. Treatment at that kind of high temperature necessitates the use of materials which are highly resistant to halogens. In addition, the 1500°C treatment of volatile halogenated Be compounds resulting from the reaction with halogen has a poor Be recovery yield, raising economic issues.

For these reasons a new program to produce the halogenated Be compounds produced from Be waste materials in order to improve Be recycling efficiency by decomposing at a temperature below 1000°C were conducted. After preliminary analysis a basic conceptual design, given in Fig.4.5.2, was created for recovering high-purity Be from impurity-containing Be materials. With this design the Be materials react with gaseous halogens (e.g., chlorine, bromine, iodine) at a temperature of at least 500°C and produce volatile compounds such as halogenated Be, which are then transferred at above 500°C by argon or helium gas containing chemically active hydrogen generated by the discharge excitation. The system proved effective in separating nonvolatile radioactive Cobalt compounds.

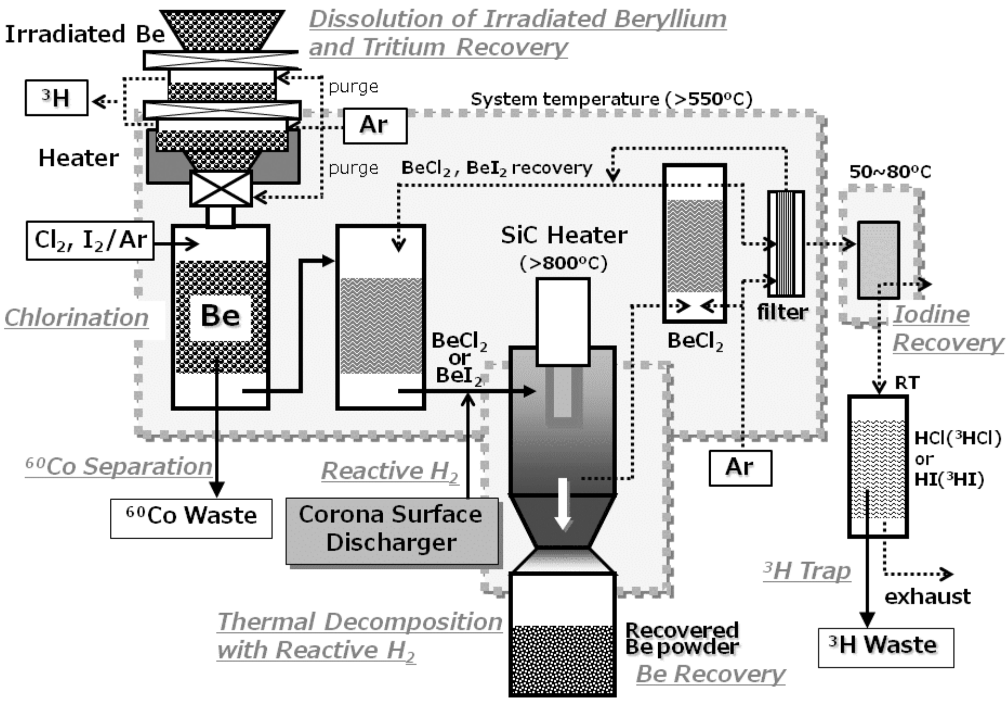


Fig. 4.5.2 Outline of the beryllium recycling system.

5. International Cooperation

5.1 Construction of World Network

To establish an international network of irradiation test after restart of the JMTR, the Center dispatched technical staff to USA (ATR; power: 250 MW), Belgium (BR-2; power: 100 MW), and the Netherlands (HFR; power: 45 MW) to discuss possible means of strengthening ties with the JMTR.

Additionally, based on a post-irradiation test program between the JAEA-KAERI (Korea Atomic energy Research Institute) cooperation, the Center has exchanged researchers for the sharing of information.

Since it shall be further effective in activity towards global standardization of these irradiation examinations, information of the present condition, future planning, irradiation technology required for irradiation tests, etc. for the main irradiation testing reactors in every country in the world is to be exchanged.

Moreover, preparation of holding of the international conference of the general-purpose irradiation testing reactor (scheduled for July, 2008) aiming at the information exchange on construction of the global irradiation testing reactor network for promoting irradiation use corresponding to globalization of users who progress quickly was started.

5.2 Cooperation Research with Studsvik AB

On December 12, 2007, "The enforcement agreement for the cooperation in the nuclear development field between Stadzvik group and the Japan Atomic Energy Agency" was concluded between the Kingdom of Sweden Stadzvik groups (Studsvik AB) and the JAEA. The signing ceremony was held in the Kingdom of Sweden Nyköping city（Fig. 5.2.1）.

The contents of the enforcement agreement are "technical development about the neutron examination in an irradiation testing reactors" promoted by the Neutron Irradiation and Testing Reactor Center , and "the radioactive waste disposal technology including recycling" promoted by a back end promotion section.

In addition, conclusion of the city friendship between a Nyköping city and Oarai-machi, was made as "a friendship city of a rainbow." at May 23, 2006.

From now on, concrete technical cooperation about the technical development for a neutron irradiation tests is due to be carried out between the Neutron Irradiation and Testing Reactor Center and the Stadszvik group.

5.3 Cooperation Research with Kazakhstan National Nuclear Center

On April 30, 2007, "The memo between the Japan Atomic Energy Agency and Kazakhstan National Nuclear Center for the future cooperation in nuclear research and development" was connected in Astana in Republic of Kazakhstan.

From now on, partnership for research between the Neutron Irradiation and Testing Reactor Center and Kazakhstan National Nuclear Center, such as technical development concerning recycling of the beryllium reflector by using of the testing and research reactor, etc, is due to be carried out.

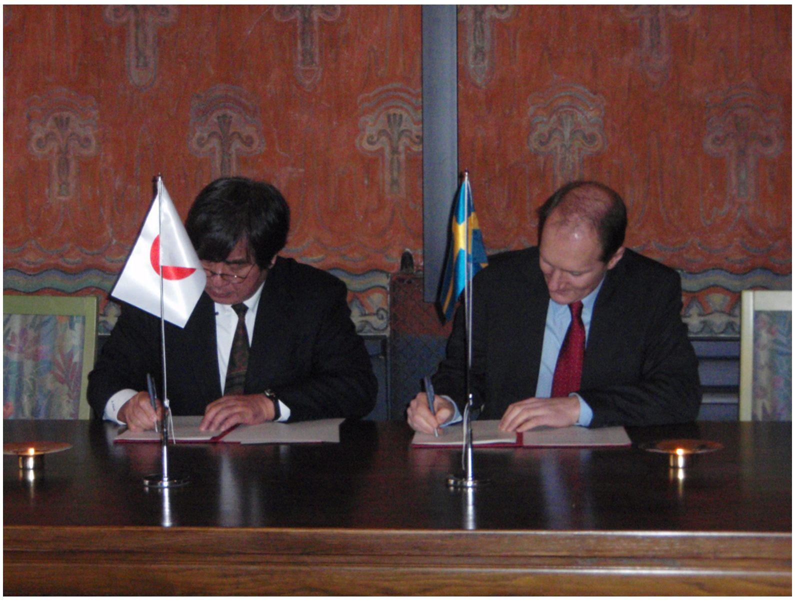


Fig. 5.2.1 Signing on implemental agreement for cooperation in nuclear energy research and development.

6. Conclusions

The report is the first in a series outlining the progress of efforts directed toward the planned restart of the JMTR in 2011. This report summarizes the results of the JMTR refurbishment, development of world-leading irradiation techniques that use the irradiation test reactor, and activities to improve the usability and accessibility of the JMTR which are carried out in 2007.

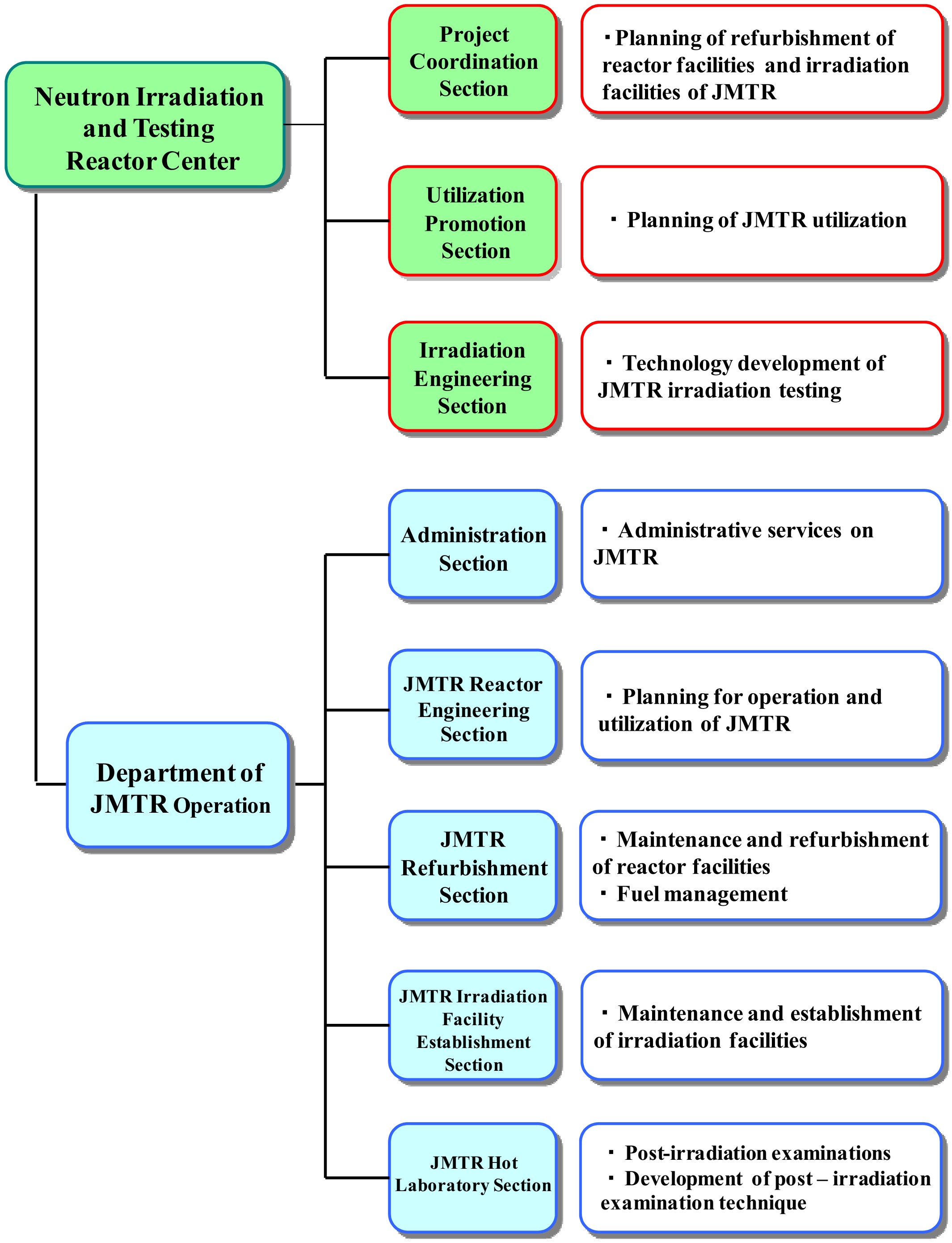
In 2008 the refurbishment projects will move into a higher gear, with the development of irradiation techniques accelerating accordingly. The Center will present a concrete operational framework for use of the JMTR irradiation capabilities.

The Center highly appreciates the reader's expectations and support in the continuing endeavor toward the eventual 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 Organization of the Neutron Irradiation and Testing Reactor Center



Appendix 2 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 is comprised of irradiation-related equipment, while the auxiliary section includes reactor utilities.

The 2007 self-imposed regular facility inspection was performed from July to December, 2008, and confirmed the sustained reactor performance and functions of the JMTR.

The 2007 mandatory regular facility inspection was carried out on the equipment that required continual performance checkups during the halt. The inspection took place over the two days of December 19 to 20, 2007 in the presence of inspectors from the MEXT (Ministry of Education, Culture, Sports, Science and Technology), similar to the 2006 mandatory inspection. The inspection verified the maintained performance of the reactor.

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 by using the hot laboratory located adjacent to the reactor. The tests have included destructive and nondestructive studies on samples irradiated in the JMTR reactor for the purpose of research and development of nuclear fuels and materials. The hot laboratory also manages the shipment of RI materials.

Hot cells can be separated into three main lines: concrete cells (β·γ-cells) including microscope lead cells, lead cells for material testing, and steel cells.

In 2007, 62 capsules were subjected to post-irradiation tests, and 23 capsules among them have completed post-irradiation tests.

2.2 Maintenance and Management

The hot laboratory facility can be divided into two main categories: the main section comprising the hot cell and hot laboratory building, and the auxiliary section that is related to the hot laboratory utilities. The 2007 self-imposed regular facility inspection was conducted from August to March, 2008, and confirmed the sustained laboratory performance and functions.

Appendix 3　Reports List on Annual Activities

Contributions to conference

N. Hori, et al., “Refurbishment of Japan Materials Testing Reactor”, International Conference of Nuclear Power of Republic Kazakhstan, (2007.9).

H. Ide, et al., “Status of Irradiation Techniques of Japan Materials Testing Reactor (JMTR)”, International Conference of Nuclear Power of Republic Kazakhstan, (2007.9).

Y. Inaba, et al., “Highly Efficient Production of Natural-Mo (n,gamma) ^{99}Mo and Practical (n,gamma) ^{99}Mo-^{99m}Tc Generator for Medical Use”, International Conference of Nuclear Power of Republic Kazakhstan, (2007.9).

K. Tuchiya, et al., “High Lithium Burn-up Test of Tritium Breeder for DEMO Solid Breeding Blanket under the ISTC Project”, International Conference of Nuclear Power of Republic Kazakhstan, (2007.9).

H. Kawamura, et al., “Recycling of Used Beryllium Irradiated in Material Testing Reactor”, International Conference of Nuclear Power of Republic Kazakhstan, (2007.9).

S. Souzawa, et al., “Development of Hydride Neutron Absorber Fast Reactor”, Annual Meeting of Japan Atomic Energy Society, (2007.9).

S. Watahik, et al., “Preliminary Evaluation on In-Core Emission Analysis in New JMTR”, Annual Meeting of Japan Atomic Energy Society, (2007.9).

K. Izumo, et al., “Overview of Refurbishment of JMTR”, Symposium on Operation, Maintenance and Improvement for the Research Reactors, Yayoi,Tokyo Univ., UTNL-R0466, (2008.3).

S. Gorai, et al., “Renewal of the reactor facilities for JMTR”, Symposium on Operation, Maintenance and Improvement for the Research Reactors, Yayoi, Tokyo Univ., UTNL-R0466, (2008.3).

K. Iimura, et al., “Design Plan of Irradiation Facility in JMTR - Mo Production by Irradiation Facility - ”, Symposium on Operation, Maintenance and Improvement for the Research Reactors, Yayoi, Tokyo Univ., UTNL-R0466, (2008.3).

T. Taguchi, et al., “Consideration for Transportation of Radioactive Beryllium Used as the Reference in JMTR”, Symposium on Operation, Maintenance and Improvement for the Research Reactors,Yayoi,Tokyo Univ., UTNL-R0466, (2008.3).

Y. Inaba, et al., “Study on ^{99}Mo production method with irradiation of circulating Mo solution(1)-Result of cold tests (preliminary tests) -, Annual Meeting of Japan Atomic Energy Society, (2008.3).

Papers

Y. Mishima[*], N. Yoshida[*], H. Kawamura, K. Ishida[*], Y. Hatano[*], T. Shibayama[*], K. Munakata[*], Y. Sato[*], M. Uchida[*], K. Tsuchiya, S. Tanaka[*], “Recent Results on Beryllium and Beryllides in Japan”, Journal of Nuclear Materials, 367-370, pp. 1382-1386, (2007.08).

K. Tsuchiya, H. Kawamura, T. Ishida, “Compatibility between Be-Ti Alloy and F82H Steel”, Journal of Nuclear Materials, 367-370, pp. 1018-1022, (2007.08).

I.L. Tazhibayeva[*], E.A. Kenzhin[*], P.V. Chachrov[*], F.M. Arinkin[*], Sh. Kh. Gasatulin[*], E.S. Bekmukhabetov[*], V.P.Shestakov[*], E.V. Chikhray[*], T.V. Kulsartov[*], A.A. Kuykabaeva[*], H. Kawamura, K. Tsuchiya, “Use of WWR-K Reactor for Long-Term trials of Lithium Ceramic Li_2TiO_3 for Fusion Reactor Blanket”, Proc. International Technical Conference “Research Reactors” (Question of Atomic Science and Technic - Fusion), pp. 3-10, (2007.09).

K. Tsuchiya, T. Hoshino, H. Kawamura, Y. Mishima[*], N. Yoshida[*], T. Terai[*], S. Tanaka[*], K. Munakata[*], S. Kato[*], M. Uchida[*], M. Nakamichi, H. Yamada[*], D. Yamaki, H. Hayashi, “Development of Advanced Tritium Breeders and Neutron Multipliers for DEMO Solid Breeder Blankets”, Nuclear Fusion, 47, pp. 1300-1306, (2007.09).

K. Tsuchiya, T. Ishida, H. Kawamura, “Effect of αBe Content on Compatibility between Be-Ti and SS316LN”, Nuclear Technology, 159, pp. 228-232, (2007.09).

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Reports

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Y. Kato, et al., “Replacement of Radiation Monitors in the Lead Cells of JMTR Hot Laboratory”, JAEA-Testing 2008-004, (2008).

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H. Ide. et al., “Fabrication of Irradiation Capsule for IASCC Irradiation Tests (2) - Irradiation Capsule for Crack Propagation Test - (Joint Research)”, JAEA-Technology 2008-012, (2008).

H. Ide. et al., “Fabrication of Irradiation Capsule for IASCC Irradiation Tests (3) - Irradiation Capsule for ECP Sensor - (Joint Research)”, JAEA-Technology 2008-013, (2008).

K. Hayashi, et al., “Technology Development on Production of Test Specimens from Irradiated Capsule Outer-tube and Mechanical Evaluation Test of Stainless Steel with High Dose Carried Out by the Technology”, JAEA-Technology 2008-016, (2008).

Y. Hanawa, et al., “Inspection of Secondary Cooling System Piping of JMTR”, JAEA-Review 2008-023, (2008).

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A. Shibata, et al., “Development of Welding Techniques for Assembling of IASCC Test Capsule”, JAEA-Technology 2008-029, (2008).

K. Iimura, et al., “Conceptual Study of ^{99}Mo Production Facility in JMTR”, JAEA-Technology 2008-035, (2008).

K. Tomita, et al., “Detaching Test of an Irradiated Mock-up Containing with Tritium from the Core of JMTR”, JAEA-Technology 2008-036, (2008).

J. Hosokawa, et al., “Conceptual Study of Silicon Semiconductor Production Facility in JMTR”, JAEA-Technology 2008-038, (2008).

Y. Hanawa, et al., “Preliminary Study for Long Life as Beryllium Reflector (1) - Fabrication of Irradiation Capsule and Dismounted Device of Capsule -”, JAEA-Technology 2008-039, (2008).

S. Gorai, et al., “Improvement of JMTR Core Management System - Applicability of SRAC2006 Code System to JMTR Core Management System -”, JAEA-Technology 2008-040, (2008).

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S. Watahiki, et al., “Development of Nicrosil-Nisil Type Multi-paired Thermocouple for High Temperature”, JAEA-Technology 2008-044, (2008).

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	$1\ µ\ =1µm=10^{-6}m$

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