V. OPERATION AND DEVELOPMENT OF FACILITIES

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1. Kyoto University Research Reactor (KUR)

The Kyoto University Research Reactor (KUR) is a light-water moderated tank-type reactor of 5MW power. Since the first criticality attainment in 1964, it had been successfully operated over than 40 years using highly enriched uranium (HEU) fuel, and served as one of the most useful inter-university research reactors in Japan.

The operation of KUR with HEU fuel ended in February 2006. Since then, the conversion processes to the use of low-enriched uranium fuel had been performed. On April 15, 2010, after the four years' shutdown, the first criticality of KUR with low-enriched uranium fuel was achieved and the KUR operation for joint research started on 28th May. The KUR operation in FY2010 was successfully conducted, and it terminated in February, 2011.

In FY2010, about 100 themes for joint research were carried out using KUR. The integrated operation time was about 1245h, and the number of clinical irradiations was 40.

2. Experimental Facilities in KUR

1) Heavy Water Neutron Irradiation Facility

The Kyoto University Research Reactor (KUR) Advanced Irradiation System has been used for Boron Neutron Capture Therapy (BNCT) organized at Heavy Water Neutron Irradiation Facility (HWNIF) which was updated at 1996. The three standard irradiation modes, namely thermal-neutrons, mixed-neutrons and epi-thermal neutrons, have been available. The clinical irradiation utilization under the full-power continuous KUR operation has been realized employing both the Radiation Shielding System consisting of the shielding door and irradiation room, and the Remote Carrying System for a patient. The safety and the utility of this facility were improved due to the Safety Observation System. Until the end of February 2011, 250 BNCT clinical irradiations had already been performed, specifically, 117 for brain tumor, 8 for melanoma, 125 for others such as the head & neck region, liver and lung using mainly epi-thermal neutron irradiation mode.

2) Graphite Thermal Column

2-1) CN-1: Cold Neutron Beam Hole

The monochromatic and well-collimated neutron beam can be used. The practical intensity is 10cps at 5MW operation. The neutron wavelength is 0.81nm with the wavelength resolution of 5%. The beam cross section is 2mm in width and 40mm in height. It has the polarized neutron option for polarized neutron reflectivity and neutron spin interferometry experiments.

2-2) CN-2: Nickel Mirror Cold Neutron Guide Tube

Relatively short (2.8 Å) wavelength neutrons are supplied to a small-angle neutron scattering (SANS) spectrometer. Therefore, the SANS spectrometer is mainly used for the structural studies of materials with the scale of 20-200Å.

2-3) CN-3: Supermirror Cold Neutron Guide Tube

Neutrons from the supermirror guide tube are used for neutron radiography and development of neutron optical devices. The critical angle of the total reflection of supermirrors is twice of that of natural nickel. The cross-section of the neutron beam is 20mm in width and 90mm in height. The peak neutron wavelength is 0.18nm. The neutron flux is $3.8 \text{x} 10^6$ n・cm^{-2}・s^{-1} at 5MW operation.

2-4) VCN: Beam Hole with Very Cold Neutron Guide

A very slow neutrons from a VCN guide tube are available as a general purpose port.

3) Hydraulic Conveyer

Hydraulic conveyer is installed at the center of the reactor core. This conveyer system is used for high-dose irradiation and isotope production of high specific activity. Irradiation ample is encapsulated in a dedicated aluminum capsule, and this is irradiated for one week at the longest. The thermal neutron flux of this system, which is the highest among the irradiation systems of KUR, is 8.2×10^{13} at 5 MW operation, and 2.1×10^{13} n/cm^2/s at 1 MW operation.

4) Pneumatic Tubes

Three pneumatic irradiation systems, Pn-1, Pn-2, and Pn-3, are installed in, the graphite reflector region, which is right outside the core. Their thermal neutron fluxes are 1.9×10^{13}, 2.7×10^{13}, and 2.4×10^{13} n/cm^2/s at 5 MW operation, and are 3.4×10^{12}, 4.9×10^{12}, and 4.2×10^{12} n/cm^2/s at 1 MW operation, respectively. By controlled CO_2 pressure, this system rapidly conveys polyethylene capsule into the core, and takes it back by back-pressure after the completion of the irradiation. For safety reason, irradiation time is limited to one hour at 5 MW, and to four hours at 1 MW operation.

5) Slant Exposure Tube

Large-sized samples are to be irradiated using the slant exposure tube, which has a thermal neutron flux of 3.9×10^{12} n/cm^2/s at 5 MW operation. This system is located at outside the graphite reflector.

6) B-1: Filtered Beam Hole

An iron-filtered beam facility, which is named beam hole B-1, is installed. This port has a 45 cm thick iron-filter and a 35 cm thick aluminum filter, to provide semi-monochromatic neutrons of approximately 24 keV energy. By transport calculation and direct neutron measurements, the neutron flux at 24 keV at 5 MW operation was estimated to be about 6.8×10^6 n/cm^2/s. The dose rates at the outer surface of the filter and at 50 cm from it are about 1 Gy/h and 0.05 Gy/h, respectively.

7) B-2: Thermal Neutron Beam Hole

A triple-axis spectrometer (KUR-TAS) is installed, and is normally used in a double axis mode with incident neutron wavelength of 0.1006 nm through a Cu (2 2 0) monochrometer for studies of magnetic materials. The following accessories are available: 1) a variable temperature cryostat down to 1.8 K, 2) high temperature furnace up to 800 K, 3) a cramp-type high pressure cell up to 3 GPa for single crystal measurements at temperatures from room temperature to 10 K, and 4) a cryostat with superconducting magnet giving vertical field up to 5 T at temperatures from 1.8 K to about 70 K.

In the future planning in the KUR, such instruments will be authorized under the opinion of low-flux neutron from the KUR reactor, and re-developed for a newly radiation instrumentation.

8) B-3: Thermal Neutron Beam Hole

A four-circle neutron diffractometer (4CND) is installed and used for investigations of precise structure determination and structural phase transitions together with a four-circle X-ray diffractometer. Incident neutrons are monochromatized to be 0.1006 nm with a Cu (2 2 0) monochrometer. Various attachments are available for regulating sample temperature from 800 K down to 4.5 K. In the future planning in the KUR, instruments will be authorized under the opinion of low-flux neutron from the KUR reactor because of a pre-check facilities against the neutron diffraction of crystals.

9) B-4: Thermal Neutron Guide Hall

Thermal neutrons are supplied through a supermirror guide tube from the reactor to this hall. The beam cross section at the guide exit is 10mm in width and 74 mm in height. The characteristic wavelength is 0.12 nm and neutron flux is $5\text{x}10^7$ n/cm^2/s at 5MW operation. It is used for neutron imaging and prompt gamma-ray analysis.

10) E-1: Exposure Hole

In this hole, facing at the side of the heavy water tank of the heavy water thermal column, an exposure plug with a narrow helical exposure tube is inserted.

11) E-2: Exposure Hole

This hole is dedicated to thermal neutron radiography mainly for non-destructive tests. Thermal neutrons are extracted from the D_2O tank and the thermal neutron flux is $1 \text{ x } 10^6$ n・cm^{-2}・s^{-1} at 5MW operation, and L/D is 100. The Cd ratio is 400. The neutron/gamma ratio is $1.1 \text{ x } 10^6$ n・cm^{-2}・mR^{-1}. The neutron beam size is 16cm in diameter.

12) E-3: Beam Hole

A prompt gamma-ray analysis system has been always installed for the detection of boron-10 concentrations in the blood for boron neutron capture therapy and the samples for the basic researches.

13) E-4: Low Temperature Loop

In order to obtain basic information on the radiation damage properties of various materials, a low-temperature irradiation facility is placed in the E-4 hole. This facility can control the irradiation temperatures to be between 10K and 400K under the maximum operating power of the KUR. The maximum fast-neutron flux is 4.8×10^{11}n/cm^2/s in the irradiation chamber.

14) T-1: Through-Tube

A horizontal through-tube in the graphite thermal column (T-1) is used for the on-line isotope separator (KUR-ISOL) of fission fragments produced by the ^{235}U(n, f) reaction. Short-lived isotopes produced in the target chamber at the center of the through-tube are transported by the gas jet system to an ion source located 11 m away from the chamber. The ionized activities are mass-separated and used both for nuclear spectroscopic studies of neutron-rich nuclides and for solid state physics.

During the shutdown of the reactor from Feb. 2006, the specifications of KUR-ISOL, especially of the target chamber, had been reconsidered in order to increase the efficiency of collecting fission fragments. In Feb. 2010, the ^{235}U target was replaced with a new one, and in FY2010, by using KUR-ISOL, a part of a project research titled "Material Science Using Short-Lived Nuclei and Radiations" was carried out, the results of which are described in the present volume of KURRI Progress Report.

15) Material Controlled Irradiation Facility (SSS)

This facility has an improved control capability of irradiation conditions, such as the irradiation temperature and atmosphere. The irradiation temperature of a specimen is between 340K and 773K. The maximum neutron fluxes are 9.4×10^{12}n/cm^2/s (E>0.1MeV) and 2.2×10^{13}n/cm^2/s (E<1eV). The maximum size of a specimen is ϕ38mm×60mm.

3. Kyoto University Critical Assembly (KUCA)

The KUCA is a multi-core type critical assembly established in 1974 as a facility for the joint use study in reactor physics for researchers of all universities in Japan. It has three independent cores, namely, two solid-moderated cores (A, B cores) and one light water-moderated core (C core). A pulsed neutron generator is also installed, which can be used in combination with the A-core.

In the KUCA, basic studies on reactor physics and reactor engineering are being performed. Recent research topics includes 1) nuclear characteristics of thorium fueled reactor, 2) nuclear transmutation studies on minor actinides, 3) critical experiments on highly-enriched uranium cores with various spectrum indices, 4) subcriticality measurements using various techniques, 5) nuclear characteristics of coupled core systems, 6) development of innovative techniques for the neutron measurement and their application to reactor physics experiments, 7) simulation experiments of the accelerator driven subcritical reactor (ADSR) using combination of subcritical cores and the neutron generator based on FFAG proton accelerator, and 8) 14MeV neutron transport in the thorium pile.

For education, the reactor laboratory course on reactor physics is offered every summer for 12 universities since 1975. Approximately 150 graduate or undergraduate students majoring in nuclear engineering are joining this course every year. The subjects offered in the experimental course includes 1) critical mass measurement, 2) control rod worth calibration, 3) measurement of neutron flux, and 4) reactor operation and fuel handling for educational purpose. The same reactor laboratory course has been offered for Korean undergraduate students from 2003 and for Swedish graduate students from 2006.

4. Electron Linear Accelerator (LINAC)

In the fiscal year 2010, the LINAC was operated for 156 days including 9 days for machine studies. The research region covered a wide field of nuclear data acquisition with the neutron time-of-flight method, isotope production with X-ray irradiation, low-temperature electron irradiation, and a spectroscopy with coherent THz radiation. Two joint research projects with private corporations have been also progressed. As minor modifications, the klystrons (model TV2022B, Thales) have been renewed to improve the operational stability of the linac. The thyratrons have been replaced from the F241 (ITT) to the L4888B (L3 comm.) for the end of life by the large grid spike. The power supply units of electromagnet for lens and steering have been moved to the klystron room in order to reduce the noise of fan in the control room.

The performance records of the LINAC in FY2010 are as follows:

i) Operation (Beam-on) time: 1,698 hrs,
ii) Total number of users: 789person-days,
iii) Number of collaboration researches: 19 (including 10 projects).

5. ^{60}Co Gamma-Ray Irradiation Facility

This facility provides equipment for irradiation of pure γ-rays from the ^{60}Co source and environment for related experiments. This facility has been utilized for a wide range of researches in physics, chemistry, biology and medical science and geological and space science. At the beginning of FY 2010, radiation activity of the ^{60}Co source was about 310 TBq and the available dose rate was about 27 kGy/h as maximum. The total operation time and the total number of irradiations in FY 2010 were about 2213.6 hours and 340 irradiations, respectively.

6. Thermal-Hydraulic Test Loop

The Thermal-Hydraulic Test Facility is open to researchers from domestic universities and public research organizations. Currently, a boiling water loop and an air-water two-phase flow loop are available. The boiling water loop has a stabilized direct current power supply of 20 volts and 5000 amperes at the maximum.

7. Neutron Mirror Fabrication Facility

(Ion Beam Deposition and Vacuum Evaporation for large neutron mirrors)

Multilayer mirror is one of the most useful devices for slow neutron experiments. It consists of alternating layers of two materials with different potential energies for the neutron. Supermirror is a stack of multilayers with gradually increasing value of the d-spacing. A multilayer with small d-spacing and supermirror with large-*m* is desirable to enlarge utilization efficiency for neutron scattering experiments. Here *m* is a maximum critical angle of the mirror in unit of critical angle of natural nickel. We have succeeded in fabricating *m*=6 NiC/Ti and *m*=5 $Fe/SiGe_3$(Si) polarizing supermirrors by using ion beam sputtering technique. The Ion beam deposition system is used for high quality neutron mirror fabrication. It has ion sources for sputtering and assist. The maximum mirror size is 20 cm diameter and the number of sputtering target is 6. The vacuum evaporation system is used for large size mirrors. Eight mirrors of 11 x 35 cm^2 can be fabricated at once.

8. Innovation Research Laboratory

In FY 2003, the Innovation Research Laboratory (LAB) was built next to the KUCA building. The LAB consists of an accelerator room, experimental area, medical area and utility rooms. The commissioning of a Fixed Field Alternating Gradient (FFAG) proton accelerator complex was completed in the accelerator room in February, 2009. At that time, a proton beam of 100MeV and 100pA was observed in the main ring of FFAG complex. This proton beam was led to the KUCA A-core to conduct the world's first experiment of an accelerator-driven subcritical reactor (ADSR) on March 4, 2009, in the framework of research project supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) starting from FY 2002.

In FY 2009, efforts have been made to improve the transmission efficiency of the beam transport system between the main ring and the KUCA A-core. The beam intensity at W target in the A-core has been increased by several tens of times compared to the previous year. On March 3, 2010, using improved proton beam, ADSR experiments with thorium-loaded core were performed.

In FY 2010, a novel H^- beam injection scheme using an 11 MeV linac as an injector has been tested with a newly constructed beam line. It uses thin charge stripping carbon foil whose effective thickness is 10μg/cm^2. No pulsed elements such as kicker magnets or bump magnets are used in this scheme. The H^- beam is injected from the outside of the main ring through the main magnet, and merged into the circulating orbit at the stripping foil. The extracted beam current from the main ring has been increased up to 1nA.

An accelerator-moderator system for the boron neutron capture therapy (BNCT) was installed in a medical area of the innovation research laboratory on March 2009. This accelerator is able to supply 30MeV proton beam of the constant intensity of 1mA over 1hour continuously. At present, characteristics of neutron field of an irradiation port achieved by this system were examined by means of physical (dosimetry of mixed radiation fields of neutron and gamma-ray) and biomedical (radiation effect and radiation safety) methods.

9. Radioactive Waste Management Facility

The radioactive waste management facility consists of several waste treatment plants, storage tanks, a waste repository, analytical instruments for examining wastes and measuring radioactivity, etc.

Radioactive solid wastes are collected and assorted by their properties (combustible, incombustible, dried animal carcasses and air filters etc.), then packaged in the drums predetermined for their properties. These drums are stored in the repository under surveillance with other wastes such as high-level liquid wastes, concentrate by evaporation, dehydrated sludge by chemical coagulation etc. described below. Parts of these wastes in the repository are delivered about once a year to the waste dealer granted legal license on radioactive waste management.

A new repository for radioactive waste storage was constructed in FY2002. The new repository with an area of about 300 m^2 has an overhead traveling crane with a maximum load of 3 tons and a control room. In addition, it should be mentioned that outdoor tanks for radioactive liquid waste storage are covered with steel-framed slate roof in FY2002.

High-level liquid wastes (higher than 3.7x10^4 Bq/cm^3) are temporarily stored for cooling at the areas of their generation till they can be handled, then stored in the repository without any condensing process. Other radioactive liquid wastes (medium-level and low-level) are treated adequately to their radioactivity and physicochemical properties as follows.

1) Evaporation

Medium-level liquid wastes (0.37-3.7x10^4 Bq/cm^3) and/or liquid wastes with high salt content are treated by the steam-heated reboiler-type evaporator that separates evaporated steam from remaining concentrate, which contains most of radioactivity in the waste. Entraining droplets are removed from steam stream by three particle separators; cyclone, packed column and perforated plate column. The evaporated steam is condensed by condensers and stored in monitoring tanks. The concentrate by evaporation is accommodated in containers. The treating capacity of this evaporation system is 0.5 m^3/h.

2) Chemical Coagulation and Freezing-and-Thawing

Low-level radioactive liquid wastes (below 0.37 Bq/cm^3) are treated by two series of chemical coagulation system, which consist of chemical tanks, rapid mixing tanks, flocculator-sedimentators, anthracite filters etc. In this treatment process, radioactive materials are removed from liquid waste into sediment slurry by chemical coagulation followed by precipitation. This coagulator has the treating capacity of 5 m^3/h for one series. Sediment slurry is dehydrated by two series of freezing-thawing process, each of whose treating capacity is 0.2 m^3/d. Dehydrated slurry is accommodated in containers. The decontaminated effluent from the coagulator is filtered by anthracite columns and stored in monitoring tanks, then discharged into the environment.

3) Ion Exchange

Two series of ion exchange system are used for low salt-content liquid waste, or also utilized for further treatment of the liquid wastes already treated by the evaporator or the coagulator, if necessary. Each ion exchange system consists of a cation exchange column, an anion exchange column, a mixed column and an inorganic-resin column. The last column is particularly capable of cesium removal. Liquid waste is treated by the proper combination of columns considering nuclides in the liquid waste. One ion exchange system has the treating capacity of 5 m^3/h. Liquid waste is purified by adsorbing ionic radionuclides onto functional groups of ion exchange resin, and the purified liquid is introduced to monitoring tanks.

The treated liquids are stored in monitoring tanks, then released into the environment after confirmation that the concentrations of radionuclides in the liquid are below the legal permissible limits.