

## V. OPERATION AND DEVELOPMENT OF FACILITIES

### 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 critical attainment in 1964, it had been successfully operated over than 40 years, and served as one of the most useful inter-university research reactors in Japan. The operation of KUR with highly enriched uranium ended on February 23, 2006. The core is to be converted to the use of low enriched uranium fuel. The safety review for a new license by the regulatory body was carried out and the license has been issued on February 22, 2008. In 2009, the KUR operation with new fuel elements of low enriched uranium will start to continue its cooperative use.

During those three years shutdown of KUR, the overhaul of most of facilities was conducted, and necessary renewal or repair of the facilities was carried out.

### 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 2006, 210 BNCT clinical irradiations had already been performed, specifically, 97 for brain tumor, 8 for melanoma, 105 for others such as the head & neck region, liver and lung using mainly epi-thermal neutron irradiation mode. After the beginning of March 2006, the HWNIF has been tentatively closed due to the temporary shutting down of the KUR.

#### 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

Short (2.8 Å) and long (5.6 Å) wavelength neutrons are supplied to a small-angle neutron scattering (SANS) spectrometer. The wavelength of the incident neutron can be easily changed. The short and long wavelength neutrons are mainly used for the structures with the scale between 20-200Å and 60-500Å. Now, we are designing a focusing SANS, which can observe the wider q-range with 2.8 Å neutron.

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

Cold neutrons from the supermirror guide tube are used for cold 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  $3.8 \times 10^6 \text{ n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$  at 5MW operation.

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

A neutron computer tomography (CT) system has been installed in VCN port. It is composed by a collimator, a goniometer for the sample rotation, a fluorescence converter and a cooled CCD camera. The sample was located on the goniometer and rotated 0 to 180° every 1° stepwise.

#### 3) Hydraulic Conveyer

The hydraulic conveyer for the high-dose irradiation and the isotope production of highly specific activity is installed at the center of the reactor core, and the sample in an aluminum capsule can be irradiated for 68 h (one week) at maximum at a thermal neutron flux of  $8.2 \times 10^{13} \text{ n/cm}^2/\text{s}$ , which is the highest neutron flux in the KUR.

#### 4) Pneumatic Tubes

There are three pneumatic systems, Pn-1, Pn-2 and Pn-3, for the neutron irradiation with a polyethylene capsule. The irradiation position is in the graphite reflector beside the core and thermal neutron fluxes are  $1.9 \times 10^{13}$ ,  $2.8 \times 10^{13}$  and  $2.3 \times 10^{13} \text{ n/cm}^2/\text{s}$  for these systems, respectively. The irradiation time is limited to be shorter than one hour.

#### 5) Slant Exposure Tube

Large-size samples can be irradiated using the slant tube with a thermal neutron flux of  $3.9 \times 10^{12} \text{ n/cm}^2/\text{s}$ . The irradiation position is at the outside of, and adjacent to, the graphite reflector.

### 6) B-1: Filtered Beam Hole

An iron-filtered beam facility was installed in the beam hole B-1 with an iron-filter of 45 cm in thickness and an aluminum filter of 35 cm in thickness to obtain quasi-monochromatic neutrons near 24 keV. The characteristic neutron spectra were studied by a transport calculation and also by measurements using a spherical proton recoil counter and activation foils. The neutron flux at 24 keV was estimated to be about  $6.8 \times 10^6$  n/cm<sup>2</sup>/s behind the filters. The absorbed doses just behind the filters and at 50 cm behind the filters were, about 1 Gy/h and about 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) monochromator 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.

The last year and in this year, instruments will be authorized under the opinion of low-flux neutron from the KUR reactor.

### 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) monochromator. Various attachments are available for regulating sample temperature from 800 K down to 4.5 K. The last year and in this year, instruments will be authorized under the opinion of low-flux neutron from the KUR reactor.

### 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  $5 \times 10^7$  n/cm<sup>2</sup>/s at 5MW operation. It is used for neutron imaging and test of detector and devices for new instrument.

### 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. In 2006, this hole was tentatively closed due to the temporary

shutting down of the KUR.

### 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<sub>2</sub>O tank and the thermal neutron flux is  $1 \times 10^6$  n·cm<sup>-2</sup>·s<sup>-1</sup> at 5MW operation, and L/D is 100. The Cd ratio is 400. The neutron/gamma ratio is  $1.1 \times 10^6$  n·cm<sup>-2</sup>·mR<sup>-1</sup>. 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. In 2006, this system was tentatively closed due to the temporary shutting down of the KUR.

### 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 was  $4.8 \times 10^{11}$  n/cm<sup>2</sup>/s in the irradiation chamber.

### 14) T-1: Through-Tube

A horizontal through-tube in the graphite thermal column (T-1) is mainly used for the on-line isotope separator (KUR-ISOL) of fission fragments produced by the <sup>235</sup>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.

In 2000, <sup>235</sup>U target was replaced with a new one and radioactive isotopes of alkali, alkali-earth and lanthanide elements have become available at the maximum ion intensity of  $10^8$  atoms/s.

In 2005, a project research titled "Production of Radioactive Nuclei and Their Application to Material Science" was carried out by using this facility.

During the shutdown of the reactor from 2006, the specifications of KUR-ISOL, especially of the target chamber, have been reconsidered in order to increase the efficiency of collecting fission fragments.

### 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 neutron flux is  $9.4 \times 10^{12}$  n/cm<sup>2</sup>/s ( $E > 0.1$  MeV) and  $2.2 \times 10^{13}$  n/cm<sup>2</sup>/s ( $E < 1$  eV). The maximum size of a specimen is  $\phi 38$  mm  $\times$  60 mm.

### 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, and 8) 14 MeV neutron transport in the thorium pile. In 2009, new neutron generating system using the FFAG proton accelerator was installed in the A-core to promote ADSR development research.

For education, the reactor laboratory course on reactor physics is offered every summer for 11 universities since 1975. Approximately 140 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 distribution, 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 2008, the LINAC was operated for 199 days including 6 days for machine studies. The research region covered a wide field of nuclear data acquisition with the neutron time-of-flight method and a lead slowing-down spectrometer, isotope production with X-ray irradiation, low-temperature electron irradiation,

and a spectroscopy with coherent THz radiation. We had no serious trouble in this period and the operation had gone well. We had four minor modifications on the accelerator in FY2008. First, the electron-tube-type trigger amplifier for the thyratron was replaced to a new system with high-power transistors to reduce the jitter of trigger timing. Second, the pulsed-high-voltage generator for the long pulse mode was renewed in order to keep the uniform distribution of electrons in a rectangular pulse even in the lower-current beam. Third, the power supply for filament heating of klystrons was changed from AC to DC in order to reduce the small amount of amplitude modulation of the RF output. Fourth, quick-released vacuum flanges, an all-metal gate valve, and a large ion pump were installed in the beam-transport section under the comprehensive support program for the promotion of accelerator science and technology from the High Energy Accelerator Research Organization (KEK).

A new operational mode with a low-energy electron beam around 10 MeV has been developed for X-ray irradiation researches.

The performance records of the LINAC in FY2008 are as follows:

- i) Operation (Beam-on) time: 2,560 hrs,
- ii) Total number of users: 1,051 person-days,
- iii) Number of collaboration researches: 19 (including 11 projects).

### 5. <sup>60</sup>Co Gamma-Ray Irradiation Facility

This facility provides equipment for irradiation of pure  $\gamma$ -rays from the <sup>60</sup>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 2008, radiation activity of the <sup>60</sup>Co source was 402 TBq and the available dose rate was 35 kGy/h as maximum. Strong radiation activity due to the source renewal in late FY 2007 keeps allowing a variety of irradiation condition through FY 2008. The total operation time and the total number of irradiations in FY 2009 were about 1750 hours and 840 irradiations. The total operation time was much less than in the previous fiscal year, because shorter irradiation time is sufficient for given irradiation dose as a result of higher dose rate.

### 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<sub>3</sub>(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<sup>2</sup> 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 the medical area, the commissioning of a 30MeV proton cyclotron was completed at the end of March, 2009, for initiating clinical trial of the boron neutron capture therapy (BNCT).

## 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<sup>2</sup> 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  $3.7 \times 10^4$  Bq/cm<sup>3</sup>) 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 ( $0.37$ - $3.7 \times 10^4$  Bq/cm<sup>3</sup>) 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<sup>3</sup>/h.

### 2) Chemical Coagulation and Freezing-and-Thawing

Low-level radioactive liquid wastes (below 0.37 Bq/cm<sup>3</sup>) 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<sup>3</sup>/h for one series. Sediment slurry is dehydrated by two series of freezing-thawing process, each of whose treating capacity is 0.2 m<sup>3</sup>/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<sup>3</sup>/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.