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## 3.7

# Present status of neutron beam facilities at the research reactor, HANARO, and its future prospect

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## Abstract

Korea has been operating its new research reactor, HANARO, since its first criticality in 1995. It is an open-tank-in-pool type reactor using LEU fuel with thermal neutron flux of $2\times10^{14}$ nominally at the nose in the $D_2O$ reflector having 7 horizontal beam ports and a provision of vertical hole for cold neutron source installation. KAERI has pursued an extensive instrument development program since 1992 by the support of the nuclear long-term development program of the government and there are now 4 working instruments. A high resolution powder diffractometer and a neutron radiography facility has been operational since late 1997 and 1996, respectively. A four-circle diffractometer has been fully working since mid 1999 and a small angle neutron spectrometer is just under commissioning phase. With the development of linear position sensitive detector with delay-line readout electronics, we have developed a residual stress instrument as an optional machine to the HRPD for last two years. Around early 1998 informal users program started with friendly users and it became a formal users support program by the ministry of science and technology. Short description for peer group formation and users activities is given.

## 1. Introduction

Since its foundation in 1959, the Korea Atomic Energy Research Institute (KAERI) has made significant contributions to the nation's nuclear technology and power development. Its first research reactor, TRIGA MARK-II of 200 kW, and the second one, TRIGA MARK-III of 2 MW, reached their criticality in 1962 and 1972, respectively. With above two reactors up to early 1992, most of research and development had been made internally and for internal purposes. The multi-purpose research reactor project started in 1985 and it reached its first criticality on February 8, 1995. HANARO, which is an acronym for the High-flux Advanced Neutron Application ReactOr, is used for the application of neutrons to a variety of fields such as physics, materials science, irradiation technology, biomedical technology, and neutron activation analysis, etc. Neutron scattering facilities are expected to meet increasing demand from both basic and applied researches that are of interest and relevance to science and technology in Korea.

When our long-term instruments development plan was made in 1992, four neutron spectrometers and a neutron radiography facility were selected to be the first phase instruments with an emphasis on structural studies such as crystal structure, phase analysis, magnetic structure, and microstructure in materials science. Since Korea has had financial difficulties for the last 3 years and the users' demand increased for the same period, the original plan was modified in late 1997 and strong demands from users were accommodated such as a neutron reflectometer and a residual stress instrument. The first phase instruments are the High Resolution Powder Diffractometer (HRPD), Four-Circle Diffractometer (FCD), Small Angle Neutron Spectrometer (SANS), and Neutron Radiography Facility (NRF). NRF, HRPD, and FCD have been in operation since 1996, 1997, and 1999 respectively, and SANS is under commissioning since September 2000. SANS at the CN beam port uses a thermal beam at present and it will be moved to a guide laboratory with proper modifications when the cold neutron source is available.

The internal and the external users started measurements and research work on the instruments in operation. Many external users have done their measurements regularly since early 1998 and the number of users from various research fields has been being increasing continuously. The first phase from 1992 to 2000 is said to be the period of the instrument development, and the second one would be the new period of balance between research and instruments development.

A brief description of the reactor, HANARO, and its cold neutron source with new activities for accelerator will be followed by the outline of the status of the neutron beam instruments development and their present utilization by the users and the other activities.

## 2. The Research Reactor, HANARO

The HANARO is an open-tank-in-pool type reactor cooled by light water, and moderated by heavy water. Its compact core inside the inner shell is surrounded by a spacious reflector, which accommodates a variety of experimental holes. The reactor core consists of 23 hexagonal tubes for H-type fuels and 8 circular flow tubes for C-type fuel assembly inside and gives room for driving a tube-type control or safety rod outside. The reactor fuel is low enriched uranium of 19.75 w/o in $U_3Si$ dispersed in an aluminum matrix with 6.35 mm diameter and 700 mm length. The core is surrounded by a heavy water reflector tank of 200 cm diameter and 120 cm height. At its maximum thermal power of 30MW, the maximum thermal neutron flux is expected to be $5 \times 10^{14}$ neutrons/cm$^2$/sec at the central thimble. In the reflector there are seven horizontal beam tubes and a total of 25 vertical holes. These holes with different sizes are widely used for radioisotope production and neutron activation analyses, and a large vertical hole for the future installation of a cold neutron source is provided. The specifications of the reactor, HANARO, are summarized in Table 1.

Table 1. The reactor characteristics

| | |
|---|---|
| Type | Open-tank-in-pool |
| Maximum thermal power | 30 MW thermal |
| Peak thermal neutron flux | $5 \times 10^{14}$ neutrons/cm$^2$/sec |
| Coolant/Moderator, Reflector | Light water, Heavy water |
| Core Cooling | Upward flow forced convection combined with bypass flow |
| Fuel | LEU 19.75 w/o $^{235}U$, $U_3Si$ in Al matrix |
| Horizontal beam ports / Vertical holes | 7/36 |
| Maximum thermal neutron flux (< 0.625 eV) | $4.5 \times 10^{14}$ nv@core,<br>$2.1 \times 10^{14}$ nv@reflector |
| Operation | 28 day×9 cycles/year |

HANARO is equipped with seven horizontal beam tubes all in tangential geometry extended from the highest thermal flux region in the heavy water reflector. Four standard beam ports (ST1～4) have 70 mm×140 mm source dimensions at the entrance and a rotating shutter/collimator unit at their exit so that one of the four options - close, open, 20' or 30' collimators - could be selected. The effective beam size at the solar collimator exit is 56 mm(W)×120 mm(H).

A cold neutron beam port (CN) is equipped with a vertical channel of 160 mm diameter with its beam tube nose of 60 mm(W)×150 mm(H) for the installation of a liquid hydrogen cold source in the future. The in-pile channel of the CN beam port is designed so that three or four neutron guides of about 20 mm width×150 mm height each could be installed reaching up to about 150 cm to the cold source. The other two beam ports are NR for neutron radiography and IR for Boron Neutron Capture Therapy.

Cold neutron source installation project were decided to be postponed by 2003 after evaluation and re-planning overall aspects including neutron guides and its laboratory, a set of spectrometers and users community. Another activity for future neutron source is for accelerator. KAERI has been performing a project named KOMAC (KOrea Multi-purpose Accelerator Complex) and its final objective is to build a 20 MW (1 GeV and 20 mA) CW proton accelerator for the accelerator driven transmutation system. In its second stage of R&D focused on the study of ADS since 1997, the low energy part to 20 MeV accelerator is to be constructed by 2003. The proposal for funding needed to build the higher energy is submitted for reviewing. Discussion for its use as a neutron source is now under discussion.

## 3. Neutron Beam Facilities

### 3.1 The High Resolution Powder Diffractometer (HRPD)

To study the structure of technologically important materials such as ceramics, alloys, superconductors, super-ionic conductors, non-crystalline materials, etc, the HRPD had been developed as a first diffractometer. Its monochromator shield unit was designed so that the two channels of the monochromatic beam can be each extracted for HRPD and FCD. It consists of multi-blocks for easy handling during installation and maintenance.

The first collimator unit consists of four collimators 6', 10', 20', and open, from which any one can be selected by rotation. A suitable filter can be installed before the monochromator in order to avoid higher order contamination. A pseudo-bent type four fold monochromator unit is adopted to select monochromatic neutrons and to focus the beam height from 200mm to about 40 mm. Ge(331), Ge(335), PG(002) and Cu(220) monochromators can be selected by rotation. Following the monochromator, there are four beam extraction units with nominal take-off angles of 44, 65, 90 and 120 degree, which have a pneumatic quick shutter at the inside face and a supplementary manual door shield at the exit face.

The Sample table, which consists of a $\Theta_S$-table, a $2\Theta_S$-table for multi-detector bank, and a $2\Theta_S$-table for the position sensitive detector (PSD) can be rotated manually around the monochromator to take one of the four take-off angles. This rotating table is strong enough to accept heavy sample environment facilities up to around 1,000 kg. The detector bank, consisting of 32 collimators of 10' and 32 cylindrical He-3 proportional counters separated by 5 degrees, moves on dance floor. Linear PSDs with 600 mm and 200 mm of active length are also available. In addition to the main powder diffraction mode, the machine can be easily converted for residual stress or texture measurement of industrial materials and real time measurements of rapidly changing phenomena with the PSDs developed in the laboratory.

As for sample environments units, a low temperature sample environment using a closedcycle refrigerator (CCR) down to 10 K and a furnace with a maximum temperature of 1,300 K are routinely available. During the last two years since early 1998, regular performance tests and normal powder diffraction experiments supporting internal and external user's research have been carried out. The fields of the users are physics, chemistry, metallurgy, ceramics, and geology, etc. We have developed an optional unit to the HRPD for residual stress measurements and the result is quite promising, and so now we are discussing with outside users to decide if dedicated instrument for the residual stress measurement should be installed.

### 3.2 The Four Circle Diffractometer

The two diffractometers, HRPD and FCD, share neutron beam from the ST2 beam port. FCD is a conventional two-axis diffractometer with an Eulerian cradle and has been be used for the structural study of single crystals and for the texture measurements for industrial applications. Ge(331), Ge(311) or (004) monochromators with a fixed take-off angle of -45 degree could be mounted with a beam height of 40mm lower than beam center of HRPD. The wavelengths of the neutron beam for the three monochromators are 0.99 Å, 1.3 Å or 1.08 Å, respectively. The effective beam size at the sample position is 20 mm in diameter.

A detector unit with a single He-3 counter is connected to the 2Θ-table by a cantilever type arm with a counter weight. The commissioning had been done by August 1999, and it is now routinely used for single crystal diffraction experiments as well as texture measurements. Two sample environments fitted with the Euler cradle such as a CCR-type low temperature cryostat and a high temperature furnace are under development. As for neutron detection, we have a plan to install a 2-D PSD and/or the image plate for fast and wide measurement in near future depending on the characteristics of requested experiments.

### 3.3 The Small Angle Neutron Scattering Spectrometer

Until the cold neutron source is available, this SANS instrument would be operated at the CN beam port in the reactor hall. Neutrons filtered by liquid nitrogen cooled beryllium are monochromatized using a high speed Dornier velocity selector to obtain neutrons with a wavelength range of 4 Åto 7 Å,. To avoid gamma radiation from the beam port in a forward direction, a liquid nitrogen cooled Bi filter or neutron V-bender with 2.635 degrees, an angular divergence of the transmitted beam, can be used in combination or independently depending on the situation. The total length of the SANS is about 8.5 m due to the limitation of the reactor hall space. The scattered neutrons is measured by using a large area 2-D position-sensitive detector of 128 × 128 pixels with a resolution of 5 mm × 5 mm.

For the design goal of $Q_{min}$~0.005 $Å^{-1}$ and a neutron intensity of $I_s > 10^4$ n/cm²/sec at the sample position, the instrumental parameters of the single-aperture collimation are optimized at a wavelength spread of $\Delta\lambda/\lambda = 0.1$. The detector can be moved continuously from 1.5 m to 5 m inside the detector chamber of 1.7 m diameter to change the available Q-range of the instrument. The whole system including the sample chamber would be evacuated down to about $10^{-3}$ torr. The $Q_{max}$ will be extended to 0.81 $Å^{-1}$ by rotating the detector up to 30 degrees around the sample stage. Its design characteristics are summarized in Table 2. The collimator with the pinhole type apertures, which are changeable with different sizes, is about 4.2 m long.

Table 2. The design characteristics of SANS

| | |
|---|---|
| Source | CN beam port without cold neutron source |
| Gamma/Fast neutron filter | Liquid Nitrogen cooled Bi/Be filter |
| | Neutron V-bender |
| Monochromator | Neutron velocity selector with variable |
| Wavelength range | speed |
| Wavelength resolution (FWHM) | 0.45 nm to 0.7 nm |
| Minimum beam divergence | 10 % |
| Sample size | 0.003 rad |
| Sample to Detector distance | 5 to 20 mm in diameter |
| Q-range | to 4.25 m |
| Detector active area | 0.06 to 8 $nm^{-1}$ |
| Calculated neutron current (n/sec) at the sample | 65 cm×65 cm with 128×128 pixels |
| $Q_{min}$ ($nm^{-1}$) = 0.06 | $2\times10^3$ |
| 0.1 | $3\times10^4$ |
| 1.0 | $3\times10^5$ |

The performance test on major components and the neutron beam characteristics of the port had been done mostly last year and an overall testing of the integrated system by SANS experiments using a one-dimensional position sensitive detector done early this year, too. The first 2-D SAS measurement had been made in August and is now under full commissioning by first quarter of next year.

### 3.4 The Neutron Radiography Facility

The neutron radiography facility was installed at the NR beam port late in 1996, as the first neutron facility at HANARO. It consists of an in-pile collimator with a Bi filter, shielding shutter and two exposure rooms. The Bi filter was put in the nose of the inpile collimator to reduce the gamma ray component. The first exposure cell is for active objects from nuclear engineering, and the second one is for general components or objects from diverse application fields. Its characteristics are summarized in Table 3.

Table 3. The instrumental characteristics of NRF

| | Exposure Room | |
|---|---|---|
| | 1st | 2nd |
| Collimation ratio | 206 | 290 |
| Thermal Neutron Flux (n/cm$^2$/sec) | $1.13\times10^7$ | $5.07\times10^6$ |
| Beam uniformity ($\sigma$) | ~7% | |
| Cadmium ratio | ~45 | |
| Neutron/$\gamma$ (n/mrem/cm$^2$) | $3.9\times10^6$ | |
| Effective beam size (cm) | 250×350 | 350×450 |
| ASTM Designation | NC-H-C = 75-8-7 | |

NRF has been used for the nondestructive testing of components from general mechanics, aerospace, ordnance industries, etc., using both the direct and the indirect methods. The training of university students related to nuclear engineering or non-destructive test is also one of the important utilization of the above instrument. The image plate usage and the real time analysis technique by image processing are also being developed and applied. In addition to this traditional radiography technique, neutron-induced auto-radiography using solid state nuclear track detectors has also been used internally and externally, such as for boron content and distribution in steel or fission fragments.

### 3.5 Others and Future Plan

Our design of the polarized neutron spectrometer at the ST1 beam port would have both a triple axis and polarized neutron beam capability in its final shape. This instrument will consist of a conventional monochromator drum which can be rotated from 10 to 60 degrees in 2Θ, a filter, polarizing crystals or a PG(002), analyzers, and spin flippers. CoFe, Heusler crystals or a polarizing mirror will produce polarized neutrons. All the tables of the sample, analyzer, and detector move on the dance floor. We have completed the preparation works such as installation of the monochromator drum and dance floor but major parts of the work for instrument development will be done during next 3 years. This instrument will be used for general test station for spectrometer component test and techniques development.

In the second phase from 2000 to 2006, a neutron reflectometer and a triple axis spectrometer, which are strongly requested by external users from universities and industries, are to be realized to extend the activity to surface/interface structure and dynamics studies. A medium resolution powder diffractometer, a dedicated instrument for residual stress measurement, or a double crystal diffractometer complementary to the present SANS is under intense discussion. In our next phase, we are going to develop several ways so that the external users can actively participate in the development of spectrometers, sample environments, and spectroscopic techniques.

## 4. Users Program and Activities

In the past before 1996, users of neutron scattering research were scattered around and not organized. KAERI scientists had been developing instruments and doing research for themselves without any serious connection with external researchers, and the number of universities researchers who could be interested in neutron scattering were very few. But since the time of reactor criticality in 1995, there had been many discussions among the researchers in the institutes and the universities. As a result, the first neutron scattering workshop could be held during June 12-13, 1997, before the commissioning of the HRPD. More than 120 participants attended and many of them became the early users of the HRPD. The 2nd workshop was held during June 11-12, 1998, before the commissioning of FCD, and about 100 participants attended. Some of the early users presented their results in this workshop.

With the increasing number of users, the first winter school focused on graduate school students was organized in February 1999. As a result of many discussions and efforts by the institute and outside users, a peer group of 15 members from universities, institutes and industry was formed in October 1999. It is to accommodate the users' demand and to make a body toward users' group or an association in the future if possible. Based on these activities and the record of experiments on operational instruments, the Ministry of science and technology decided to support the users outside the institute in December 1999 and 18 grants were awarded mostly to the university groups. If this trial program worked successful, we could expect a strong, long-term program, which would boost up the neutron scattering research in Korea.

The 3rd neutron scattering workshop (February 16-17) and 2nd winter school (February 18-19, 2000) were organized jointly by the KAERI, the Korea Advanced Institute of Science and Technology (KAIST) and the Garcia Center at the State University of New York at Stony Brook. The subjects were small angle neutron scattering and reflectometry from soft matter. A one-day tutorials on SANS and reflectometry in the winter school for about 100 graduate students was given by the well-known experts in the field.

More and more researchers are now visiting the HANARO site and Pohang Synchrotron is also available for them. We, therefore, could hope to make strong scattering research community within a short time. By now most of the experiments have been limited to powder diffraction and single crystal diffraction related fields. Small angle scattering works could be included next year depending on the availability of the instrument and then the users' community would be expanded more rapidly.

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