

OPPORTUNITIES AND CHALLENGES OF NEUTRON SCIENCE AND TECHNOLOGY IN KOREA

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Neutron science and technology, the utilization of neutron beams for a wide variety of scientific and engineering research ranging from materials and life science to industrial applications, has been one of the key elements of modern science and technology. Currently, the neutron science and technology in Korea is in rapid growth with the operation of the 30 MW High-flux Advanced Neutron Application Reactor (HANARO) at the Korea Atomic Energy Research Institute, which is one of the most powerful nuclear research reactors in the world. Furthermore, a state of the art HANARO cold neutron research facility, which will open a new era for the neutron science and technology in Korea, is expected to become available in 2010. In this paper, the progress of neutron science and technology in Korea is reviewed and its unprecedented new opportunities and challenges in coming years are presented.

KEYWORDS : Neutron Science and Technology, Nuclear Research Reactor, Cold Neutron

1. INTRODUCTION

Neutron science and technology, the utilization of neutron beams for a wide variety of scientific and engineering research ranging from materials and life science to industrial applications, has been one of the key elements of modern science and technology. The utilization of neutrons for materials research first started with Wollan and Shull in 1946 after high intensity slow neutron beams became available after the discovery of nuclear fission and self-sustaining nuclear chain reaction [1]. Since then, the intensity of neutron beam available has been increased greatly and various new neutron techniques have become available. With this progress, neutrons have been used as an indispensable tool to investigate the atomic and nanoscale structures and dynamics of materials that have paved the way to develop new technologies. It is expected that the contribution of neutrons to new science and technology, which require more detailed information and understanding of materials, will become more important throughout the twenty first century.

In Korea, the field of neutron science and technology began with the TRIGA Mark-II nuclear research reactor

which started its operation in 1962. Currently, the neutron science and technology in Korea is in rapid growth with the operation of the 30 MW High-flux Advanced Neutron Application Reactor (HANARO) at the Korea Atomic Energy Research Institute, which is one of the most powerful nuclear research reactors in the world. Furthermore, a state of the art HANARO cold neutron research facility, which will open a new era for the neutron science and technology in Korea, is expected to become available in 2010. In this paper, the progress of neutron science and technology in Korea is reviewed and its unprecedented new opportunities and challenges in coming years are presented.

2. DEVELOPMENT OF NEUTRON SCATTERING INSTRUMENTS

TRIGA Mark-II, the first research reactor in Korea shown in Figure 1, started its operation at 100 kW in March 1962 and upgraded to 250 kW with the maximum thermal neutron flux slightly less than 1.0×10^{14} n/cm² s in June 1969. Although the main purpose of TRIGA Mark-



Fig. 1. TRIGA-Mark-III Nuclear Research Reactor

It was training and radioisotope production, it had 4 horizontal beam tubes for neutron beam research. A neutron diffractometer was installed and the crystal structures of various materials, including NaCl, were analyzed. Prototype neutron imaging experiments were performed in the thermal column.

Since 1972, TRIGA Mark-III had produced $6.5E13$ n/cm^2 s of maximum thermal flux. A reverse filter type spectrometer was installed where inelastic scattering spectra of powder samples such as $NaBr \cdot 2H_2O$, $BaCl_2 \cdot 2H_2O$, L-Serine was measured. A double axis diffractometer was installed for the crystal structure analysis of powder and single crystal. However, it had been mainly used for metallic texture measurement due to the limitation of neutron flux level. A triple axis polarized neutron spectrometer, which was imported from BARC, India in 1983, was used to study basic techniques such as production of polarized neutrons through $Co_{0.92}Fe_{0.08}$ or magnetized mirrors, and neutron spin control with RF spin flippers. The time-of-flight spectrometry had been studied through the spinning crystal type spectrometer.

A neutron radiography facility was installed in 1983 and an imaging technique by solid state track detection was developed. With the high penetration of neutrons into nuclear materials including H, Be, B, Al, Zr, Cd, and Pb, this imaging technique was mainly used for non-destructive testing of nuclear fuel and components.

The 30 MW HANARO research reactor, which was the first research reactor designed by KAERI [2], became critical in 1995. Since then, HANARO has been the only research reactor that provides high intensity neutron beam with a peak thermal neutron flux of 5.4×10^{14} n/cm^2 sec.

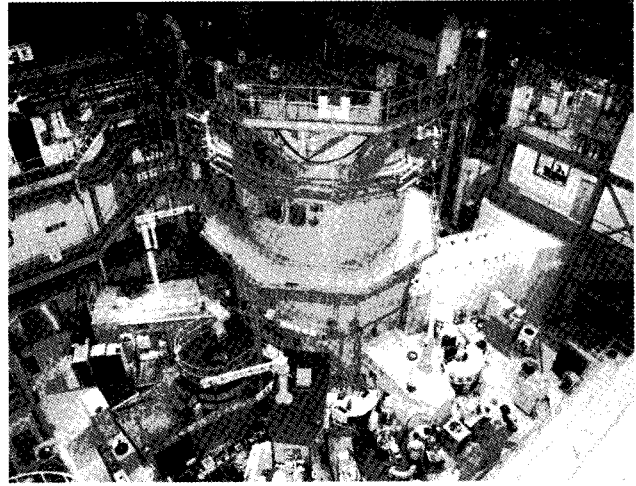


Fig. 2. HANARO Reactor Hall with Neutron Instruments

Initially, the primary purposes of HANARO were to do irradiation tests of nuclear fuel and materials and to produce radioisotopes. Later, neutron beam research and radiation utilization research were added to the main purposes of HANARO. Now neutron beam research is the most important research for HANARO. Described below are the neutron instruments that are in operation in the HANARO reactor hall (Figure 2).

2.1 High Resolution Power Diffractometer

The high resolution power diffractometer (HRPD), which measures crystal structures of powder samples, started its public operation in November 1997 and currently has the highest number of users among the neutron instruments at the HANARO. It covers a wide range of research areas including crystal structures, texture and residual stress analysis, and phase transition of superconductor, magnetic material, and magnetic resistance materials. Several sample environments such as CCR(10K-300K), Vacuum Furnace (RT-1200K) and Magnet+CCR (0.85T/10K) are available for studying structural and magnetic phase transitions.

From neutron powder diffraction patterns, one can obtain information about the positions and thermal behaviors of light elements (H, Li, C, O etc.) contained in heavy element compounds. One can also investigate the substitution effects between transition metal and lanthanide groups as a complementary tool of X-ray diffraction. By the virtue of the inherent property of neutron, high transmission due to its weak interaction with matter, neutron diffraction can also be used to study the bulk properties of specimen and to do quantitative phase analysis of bulk specimen (including powder), even though it takes a much longer time and one needs a much larger amount of sample than X-ray diffraction.

2.2 Small Angle Neutron Scattering Instrument

Small angle neutron scattering (SANS) is a very powerful technique to investigate nano-scale (1–100's nm) bulk structures in a broad spectrum of materials including polymers, complex fluids, bio-materials, ceramics, metals, flux line lattice in superconductors, and magnetic materials. In the major neutron research facilities in the world, SANS has been the most popular instrument among cold neutron instruments and often two or three SANS instruments are available in a neutron facility (ex. NIST, ILL, and ORNL).

Understanding the importance of the SANS technique, the HANARO neutron physics group started to build a 8m SANS instrument at the CN beam port inside the confinement building in the late 1990s and finished its commissioning in 2001. [3] Since the 8m SANS instrument utilizes the low energy tail of the Maxwellian neutron spectrum without a cold neutron source, the beam intensity is fairly low and the Q-range is rather limited due to short instrument length. However, it has been a very valuable instrument for studying samples with strong neutron scattering contrast and very successful in promoting domestic neutron user community. Also, it has made HANARO personnel well equipped with techniques and skills necessary to build a state-of-art SANS instrument and to upgrade the 8m SANS to a 12m SANS. The 12m SANS instrument with a cold neutron source will be an essential tool in various branches of science and engineering in Korea, providing a non-destructive nano-scale measurement technique.

2.3 Vertical Neutron Reflectometer

Neutron reflectometry (NR) is a technique for probing the surface and buried interface of thin films with a 1–500 nm thickness by measuring the reflected neutrons at a glancing angle from the surface. The technique can also be used to examine characteristics such as thickness, surface and interfacial roughness, composition, and any defects with a resolution down to 10 Å along the depth direction. Since the technique was proposed by Hayter in 1981, it has been widely used to study surface physics, surface chemistry, solid films, and surface magnetism. Neutrons interact with nuclei in matter. As a result, they can be used to study the buried interface that is not easily accessible to other techniques. It is possible to study the structure of materials under a sample environment such as a closed-cycle refrigerator (CCR), a furnace, and high pressure devices. Because neutrons have a magnetic moment, they can interact with unpaired electrons in magnetic atoms. This magnetic scattering can be used to elucidate the magnetic structure of various materials. In particular, PNR (polarized neutron reflectometry) has become an increasingly powerful method for the study of materials for advanced devices in the field of spintronics in recent years.

A neutron reflectometer with vertical sample geometry (REF-V) was installed at the ST3 thermal beam port at

HANARO in 2006. The instrument utilizes 2.45 Å neutrons monochromatized by a PG crystal. Even with this limitation of low wavelength, the reflectivity as low as 10^{-6} was determined. [4] Later this year, this instrument will be moved to the cold guide hall and its performance is expected to increase dramatically.

2.4 Four-Circle Diffractometer

A four-circle diffractometer (FCD), which measures single crystal structures and textures, was installed at the ST2 beam port at the end of 1999. Typical applications of the FCD include measurements of hydrogen distribution, molecular disordering, and atomic and magnetic structures. It also serves for structural studies of materials related to ceramic and macro-molecule crystallography. The FCD, which shares neutron beam with the HRPD by having its beam center vertically shifted by 40 mm from the beam center of the HRPD, has a mosaic Ge(331) monochromator (with a fixed take-off angle of -45°) between the ST2 beam gate and the first collimator unit inside the main HRPD shielding. The neutron wavelength from the monochromator is 0.997 Å and the effective beam size at sample position is 30 mm in diameter.

Upgrade of the FCD started in late 2004 to improve its data quality and data collection time and to expand its research fields. In 2006, almost full range of modifications had been made and various new features were added to the FCD from the monitor area to the detection parts. Modifications were also made for the instrument control program except the monochromator part. A variety of environments for crystal sample setting and alignment, instrument monitoring, safety interlock have also been improved. A CCR-type low temperature cryostat and a high temperature furnace allow temperature dependent structure investigations in the temperature range from 10K to 300K and from 300K to 1300K.

2.5 Prompt Gamma Neutron Activation Analysis

The prompt gamma neutron activation analysis (PGNAA) instrument at HANARO, which determines the presence and amount of many elements simultaneously in samples, consists of crystal assembly, collimators, shields for background neutrons and γ -rays, and beam catcher. The LiF tiles are attached to the inner sides of the lead wall to reduce the effects of the scattered neutrons and 95% enriched ^6LiF tiles are attached to the front of the detector. The detection system initially comprised of a single HPGe (43%), signal electronics and a fast 16k ADC. The sample-to-detector distance is 25 cm. In 2002, a NaI(Tl)-BGO guard detector and the associated electronics were installed, and the detection system was upgraded to Compton-suppressed and pair spectrometer with three modes of detection: single, Compton-suppressed, and pair modes. With several modifications, including a reduction of the collimator aperture in front of the detector, the total background count rate has been reduced by a

factor of 10 at the expense of about a quarter reduction in the full energy peak efficiencies. Hence a better sensitivity of the spectrometer with a reduced dead time in ADC could be achieved [5,6].

2.6 Neutron Radiography

Neutron radiography utilizes the interactions of neutron with nucleus which provide unique neutron cross-section with respect to all of the elements in the periodic table. Even radioisotopes of the same element can be distinguished by the neutron radiography due to its specific cross-section. In comparison to x-ray, neutrons could penetrate deeply into the material, even if it is a heavy element, because it can interact with nucleus, not orbital electrons. Neutron radiography is recognized as a complementary technique to X-ray and gamma radiography. The neutron spectrum is highly thermalized, which allows for high quality imaging. A hydrogen facility was installed for measuring fuel cell images. Neutron radiography is an excellent tool for non-destructive inspection of electronic, mechanical and ordnance parts and assemblies. The neutron radiography facility at HANARO is often used for non-destructive inspection of various parts and assemblies from industries and other sectors, including air-cooled jet-engine turbine blades, archaeological artifacts, high-reliability explosives, airframe sections, and nuclear fuels. Residual stress instrument, high intensity powder diffractometer, ex-core neutron-irradiation facility are also in operation.

3. COLD NEUTRON RESEARCH FACILITY AND COLD NEUTRON INSTRUMENTS

The 30 MW HANARO research reactor at the Korea

Atomic Energy Research Institute is a world class research reactor with a peak thermal neutron flux as high as 5.4×10^{14} n/cm²/sec. However, its potential impacts on scientific and engineering research in Korea have been limited by the lack of a cold neutron source and cold neutron instruments. To overcome this, a HANARO cold neutron research facility project was formulated through a feasibility study [7] in 2002 and project planning [8] in early 2003. In July 2003, the cold neutron research facility project supported by the Ministry of Education, Science and Technology was launched. The project scope includes the installation of a cold neutron source and its supporting systems, neutron guides, relocating three existing instruments, and installing three new instruments: a 40 m SANS instrument, a cold triple-axis spectrometer, and a disk chopper time of flight spectrometer (Figure 3). The three new instruments were selected based on a domestic user survey. In parallel with this project, an ultra small angle neutron scattering (U-SANS) instrument is being developed by KIST. A cold neutron laboratory building (Figure 4) has been constructed by a separate funding source in November 2008.

3.1 40 m Small Angle Neutron Scattering Instrument

The SANS instrument is a very powerful tool to investigate nanoscale bulk structures in a broad range of materials, making it the most popular instrument among cold neutron instruments. While the current 8 m SANS has been very useful, its accessible q-range has been severely limited by its short flight path. To overcome this limitation, a state of the art 40 m SANS instrument is being developed as a collaborative project between HANARO and the Korea Advanced Institute of Science

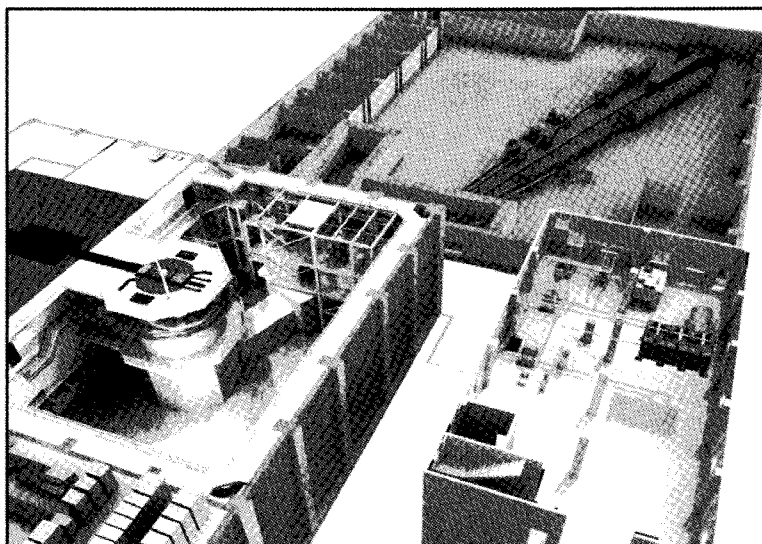


Fig. 3. Schematics of the HANARO and Cold Neutron Research Facility



Fig. 4. Cold Neutron Laboratory Building

and Technology (KAIST). The 40 m SANS instrument consists of a neutron velocity selector, a 20 m pre-flight path with a removable collimator system, a sample area, and a 20 m long detector vacuum tank that contains a $1 \text{ m} \times 1 \text{ m}$ position sensitive He^3 neutron detector [9]. Its accessible q -range is 0.0005 \AA^{-1} - 1.0 \AA^{-1} , making it one of the most competitive SANS instruments in the world. The design of the 40m SANS is completed, and currently, its fabrication and installation are well in progress. Once the 40 m SANS is commissioned in early 2010, it will be a key instrument for a broad range of nanoscale materials research in Korea including polymeric materials, complex fluids, biomaterials, engineering materials such as metals and ceramics, and condensed matters such as superconductors and magnetic materials.

3.2 Cold Neutron Triple-Axis Spectrometer

Neutrons excel at observing magnetic moments because neutrons have spin 1/2 themselves and interact with magnetic moments directly. Combined with the fact that cold neutrons have energies comparable to that of low energy excitations in exotic materials such as quantum magnets, cold neutron spectroscopy is regarded as one of the most powerful tools to observe low energy spin dynamics which have become important these days to test the newest theories on solid state physics.

One of the two new such spectrometers in the guide hall, the cold neutron triple-axis spectrometer, was given the whole of CG5 guide which is 50 mm wide and 150 mm tall. The guide uses $m=2$ supermirror everywhere and has the radius of curvature of 1500 m in the curved section. The instrument will use two sets of vertically

focusing monochromators and horizontally focusing analyzers: PG(002) for maximum intensity and Heusler (111) for polarized neutrons. Originally the instrument was expected to be complete in 2010, but the budget short falls might delay the project for almost a year. Once completed, the instrument would be best used with single crystals of various magnetic materials, although other low energy excitations can also be pursued on this instrument.

3.3 Disk Chopper Time-of-Flight Spectrometer

The disk chopper time-of-flight spectrometer (DC-TOF) measures dynamics of materials such as translational and rotational diffusion process, low energy vibrational excitations, densities of states, and tunneling phenomena. The DC-TOF at HANARO, which is being developed as a collaborative project between HANARO and SKKU, consists of 6 disk choppers, a sample stage, and a detector bank. The first and the last chopper housings contain fast counter rotating choppers with a maximum speed of 20,000 rpm, and the second and third housings contain slow single choppers with a maximum speed of 12,000 rpm. The total flight path between the first and last chopper is 12.0 m. A super-mirror guide will be used for focusing section in the elliptical shape. The total length of focusing part is 12.7 m. The m -value becomes larger as it approaches the exit. 352 one-dimensional position sensitive detectors (1D-PSDs) were designed to be installed along the outside of detector tank. In the commissioning time, only some fraction of the detectors will be installed. Detector electronics are now developed under collaboration with KASI (Korean Astronomy and Space Science Institute). A gas filled type detector tank and a vacuum sample

chamber were also designed. Between them, Al-windows will isolate their vacuum. 1D-PSDs will be located in the detector tank. Data reduction software is being developed under J-PARC and KAERI collaboration. Data acquisition and control software is developed under KAERI-Kyungbook National University collaboration.

3.4 Bio-Reflectometer

Bio-reflectometer (Bio-REF) is a horizontal type neutron reflectometer that can measure liquid-solid and liquid-air interfaces, allowing the studies of bio-membranes and protein-membrane interactions. The Bio-REF at HANARO, which is being developed as a collaborative project between HANARO and Sogang university, is designed to meet high demands on the following conditions, i) high q -range with the liquid/solid interface (e.g., lipid bilayers) and ii) access of the air/water interfaces (e.g., Langmuir monolayers) for the comprehensive investigation of biological application, in addition to the classical depth profiling techniques for the polymeric thin films. In order to meet these demands, the Bio-REF has been designed to have dual geometries, i) a high- q accessible th - $2th$ mode for the solid based interfaces, and ii) a limited- q , but free surface accessible th - th mode, respectively. In order to maximize the neutron flux, a monochromatic beam will be selected by a ZYA PG monochromator tilting stage that is stacked with 4 monochromators with 0.5° spacer between the monochromators. Neutron guide elements between the monochromator to sample stage, and sample stage to detector were designed for realizing minimum beam loss. Two types of detectors, a pencil-type detector for the solid sample, and a position sensitive detector for the free surface, are currently being designed. The machine can rotate to be accessible to the inside of shielding, providing a clear view for the slit and monochromator from outside. Currently, an engineering drawing for the tilting stage for the monochromator has been finished, and sample environments for experiments at the air/water interface, as well as at the air/solid and liquid/solid interfaces, are under development.

3.5 Vertical Neutron Reflectometer

The vertical neutron reflectometry is a technique that is sensitive to the depth-dependent composition and in-plane structure of thin films. The vertical neutron reflectometer at the HANARO reactor hall will be relocated to the cold neutron guide hall with some modifications. A focusing monochromator composed of 7 pieces of PG will be used, which is expected to increase the neutron flux by a factor 3 compared to the flat single monochromator. In order to eliminate second harmonic due to the PG monochromator, a neutron filter made of Be crystal immersed in liquid nitrogen is designed and will be placed between the focusing monochromator and the first slit in monochromator shielding. Currently, a monochromator shielding is being designed to satisfy the conditions above

and a motor control system, which drives 24 motors in the instrument, is being upgraded.

3.6 12 m Small Angle Neutron Scattering Instrument

The current 8 m long SANS instrument at the CN beam port at HANARO will be relocated to the cold neutron guide hall and will be upgraded to a 12 m long instrument by early 2010. The 12m SANS instrument will be located at the end of neutron guide CG4A where the guide cross section is $50 \text{ mm} \times 50 \text{ mm}$. This is a medium resolution SANS instrument suitable for examining structural features in materials from roughly 1 to 100 nm, covering q -range of ca. 0.004 \AA^{-1} - 0.5 \AA^{-1} .

Neutrons from the cold source pass through a mechanical velocity selector with variable speed and pitch, enabling both the mean wavelength and wavelength resolution to be varied over a wide range. The monochromatic beam is collimated by two circular pinholes in a 6 m long evacuated collimation flight path. The source pinhole can be preceded by up to two 2 m guide sections that can be easily shifted in or out of the beam. Choices of beam apertures will be automated. The beam divergence and flux on the sample can thus be varied by changing the effective source-to-sample distance from 2 to 6 m in 2 m increments. The post-sample flight path consists of a cylindrical section that forms a vacuum enclosure for a large 2D position-sensitive detector. The area detector moves along rails inside the cylindrical vessel to vary the sample-to-detector distance from 1 m to 6 m. In addition, the detector moves

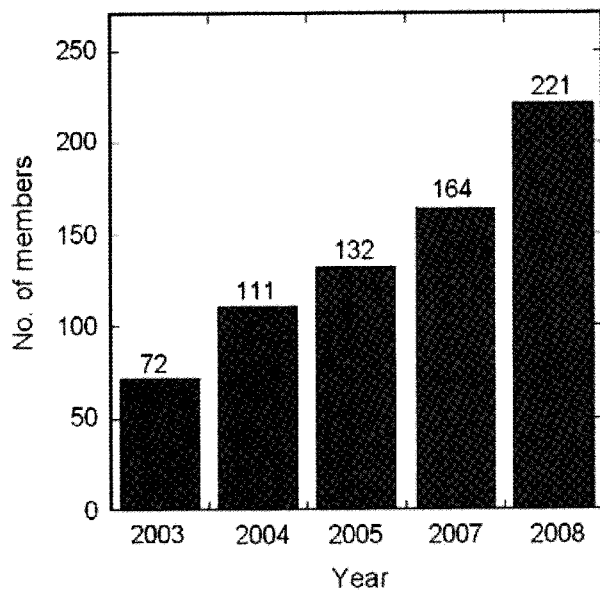


Fig. 5. Growth of Members of the Korean Neutron Beam Users Association

transversely to the beam direction to extend the Q range covered at a given detector distance. The instrument control system and data collection procedure will be automated and user friendly. A sample table with enough space will be prepared to implement various sample environments and to allow easy access, but with minimal air path length. Some space will be reserved for the addition of foreseeable new instrument options.

4. NEUTRON USER COMMUNITY: GROWTH AND ROLES IN KOREA

The HANARO neutron research facility is a national user facility that requires a strong user group as one of the key elements for its success. There has been a surprisingly long history of neutron scattering in Korea which dates back to the early 1960's, but the scattering technique was reserved to a privileged few since the research reactors of that time were not powerful enough to attract users. The operation of the HANARO was a huge turn-around. The 30 MW-reactor is a multi-purpose reactor suitable for many applications such as irradiation tests, radioisotope production, and neutron beam research. Most importantly, however, it boasts one of the highest neutron beam flux in the world. Many users began coming to HANARO to perform serious experiments since the reactor went critical in 1995. In 2000, a neutron special interest group as a part of the HANARO Users Association was formed to promote neutron science and to communicate effectively with HANARO. In 2003, the Korean Neutron Beam Users Association (KNBUA) was formally found and its membership saw a significant growth after the HANARO Cold Neutron Research Facility project was launched. The membership has been more than tripled since 2003 and the total number of members now exceeds

220 (Figure. 5). It is expected that there will be a jump in the number of members once the HANARO cold neutron research facility starts its operation.

The KNBUA, as a whole, is engaged in many activities that promote neutron science in Korea. First, for its academic activities, it organizes or sponsors neutron science related workshops. These workshops are mostly organized through the four topical groups that the association is made of: the elastic group, the inelastic group, the low-Q group, and the radiography group. Some examples of those workshops are the annual Workshop on Neutron and X-ray Scattering Techniques for Surface Nano-Characterization, the Annual Meeting on Inelastic Neutron Scattering, and many other occasional workshops that members host.

Second, the KNBUA advises the HANARO management on various operational and user-related issues. Now that the completion of the cold neutron facility project (CNRF) is approaching, one of the most important issues at HANARO these days is to find the best way to operate the facility for maximum output. In this regard, the KNBUA-HANARO joint brainstorming was held in 2007. As a result, the two parties confirmed that the HANARO neutron beam facility is a national user facility and to ask the government to fund it adequately.

Third, it promotes neutron science to the government and the industry by using various channels. After the brainstorming mentioned above, the KNBUA recommended the government to launch a policy study on how to operate and use the facility properly once the CNRF project is finished. It is very important that the recommendations made in the policy report, which was recently completed, is followed through by the government and HANARO.

Fourth, the KNBUA promotes education of users by organizing tutorials or schools such as the Winter School on Neutron Small Angle Scattering and Reflectometry

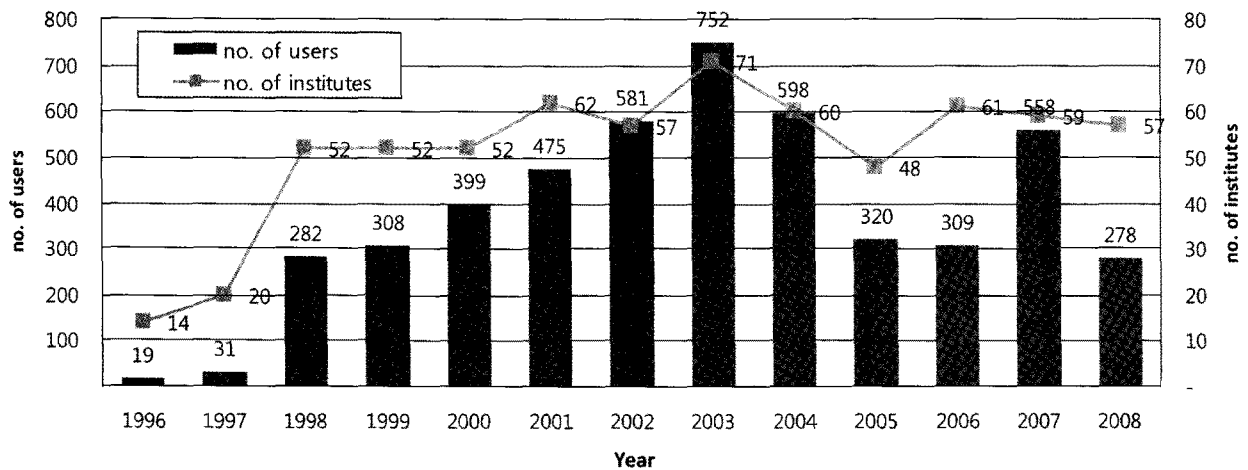


Fig. 6. Number of Neutron Users at HANARO

held at KAIST, which helped in promoting the HANARO user education program and sponsoring student training. Several students, annually, are sponsored to attend overseas neutron scattering training courses.

Lastly, the KNBUA is actively engaged in international collaborations by organizing international meetings such as the annual Korea-Japan meeting and by communicating with the other societies. Most importantly, the KNBUA played a leading role in founding the Asia-Oceania Neutron Scattering Association (AONSA) to promote neutron science and technology in the Asia-Oceania region. The AONSA, formed in 2008, is an affiliation of neutron scattering societies and communities that directly represent neutron users in the region. Currently, the president of the KNBUA is serving as the first president of the AONSA. In August 2008, the KNBUA and the HANARO co-hosted the 1st AONSA Neutron Summer School at KAIST that was attended by students and young scientists from 8 countries in the region.

5. SCIENTIFIC RESULTS OF THE HANARO NEUTRON FACILITY

Over the years, the HANARO neutron science facility has been utilized by many users from universities, research institutes and industries (Figure. 6) and has produced many publications. Following are some of the representative results obtained by using the facility.

Although the 8m SANS instrument had been attached to a thermal beam port until 2008, thus with very limited cold neutron flux, it still proved to be a valuable tool to soft-condensed matter scientists in Korea. For example, a closed-loop phase behavior of block copolymers, deuterated polystyrene-*block*-poly(*n*-pentyl methacrylate) copolymers [dPS-PnPMA], was observed under hydrostatic pressure, and the pressure dependence of the phase transition temperatures were found [10]. The SANS instrument played a key role in observing this behavior. In another example, the instrument was utilized to observe the change in the size distribution of vesicles upon the introduction of an amphiphilic polymer, PEG-DMPE [11], and the uniaxial alignment of discotic columnar liquid crystals by an applied magnetic field [12]. It is worthwhile to mention that the instrument has been useful in studying more application-oriented materials such as boron-added steel. [13]

As in many other facilities, the HRPD is widely used by those who want to know the structures of newly synthesized materials. Some of the more well-known examples are BiFeO₃-PrFeO₃-PbTiO₃ solid solutions and BiFeO₃-ReFeO₃-BaTiO₃ solid solutions (Re=Dy, La) which show ferroelectric and ferromagnetic properties concomitantly at certain compositions [14,15], and Sr_{1-x}Bi_{2-4y}Ta₂O₉ ceramics for their relationship between structure and ferroelectricity [16]. More recently the instrument has been utilized in probing chemical systems

such as clathrate hydrates and superconductors such as DyB₄ [17,18]. The other crystallographic instrument, the FCD, meanwhile, has been useful in generating pole figures when studying the texture of alloys [19].

As the previous examples show, the scattering instruments are geared more toward science. On the other hand, the neutron radiography has been successfully applied in a diverse field of applications such as engineering, agriculture, archaeology, and non-destructive inspections. A notable example was the inspection of the old and new national seals in 2005 and 2007 respectively. The old seal was found to have a few cracks inside, forcing the government to make a new one and have it inspected by using neutron radiography. Meanwhile the prompt gamma activation analysis technique has also advanced steadily [20,21].

6. PERSPECTIVES OF NEUTRON SCIENCE AND TECHNOLOGY IN KOREA

A recent policy study on the utilization of HANARO neutron facility identified new opportunities and challenges that HANARO and Korean neutron science and technology community face in coming years [22]. This was done through extensive investigations on the current status and future needs, and through a series of advisory meetings. The following is a summary of the policy study contributed by domestic and internationally leading neutron scientists, especially Dr. J.M. Rowe.

With the completion of the cold neutron research facility project, HANARO will provide an exciting opportunity for the entire science and technology community in Korea. HANARO has established an outstanding operating record during the last ten years of operation, and the neutron intensity provided for neutron beam research is highly competitive with other research reactors around the world. The new cold source that is being constructed and installed will undoubtedly provide cold neutron beams that can support internationally competitive research at the forefront of physics, chemistry, materials science, and biology. The new cold neutron instruments will provide world-class performance. This all points to the potential for a research program that is internationally competitive, provided that the resources being developed are properly exploited. There is a well-trained cadre of actual and potential users of the HANARO neutron facility that has been developed by using foreign neutron sources as well as HANARO, and a much larger community of potential users who have not had the opportunity to use neutron techniques.

The potential scientific payoff of these new capabilities is greatest in areas of high current interest for both scientific and technological reasons. Cold neutrons are well suited to studies of polymers, biomaterials, spintronic materials, where the long wavelength and low energy of the neutrons are

well matched to the lengths and time scales of the systems to be studied. The capabilities neutron instruments at HANARO should be fully competitive with those at other internationally leading neutron facilities around the world.

However, this potential can only be realized through the development of a high quality user program at HANARO that engages the full talent and capabilities of the Korean academic and industrial research communities. This will require operating the neutron scattering program as a national user facility, following the model in operation at all of the major neutron scattering centers in the world and most synchrotron radiation facilities. This model is distinguished by several distinct characteristics:

- High quality instruments and sample environments
- High quality scientific and technical support for users
- Broad-based access on the basis of scientific and technological merit
- Access without user fees for research currently published

Recent studies have shown that the productivity of large facilities and even individual instruments at internationally leading neutron facilities is directly correlated with the level of support, up to a saturation point set by the characteristics of the instrument. This model also ensures that the best research is done by competitive, merit-based access, thus maximizing the return on the large initial investment to provide a high quality facility. The validity of the model is now generally accepted world wide, and has led to enhanced support for user operations over the past 5 years.

The present arrangement at HANARO simply cannot support a national user facility mode of operation. The scientific staff is small, and dedicated to agency mission related research, and thus unable to provide adequate support for users. The results are evident in the productivity of the current instrument suite, and there is no doubt that this will also be the fate of the new cold neutron instruments, barring a major national decision to properly support operation as a national facility. However, it is equally certain that proper support will lead to an internationally competitive operation, providing Korean researchers with a powerful new suite of research and measurement tools to support future technology.

Overall the HANARO neutron research facility as of now is strong in neutron instruments, providing new opportunities for neutron science and technology in Korea, but it is not adequately funded or manned to operate as a national user facility. This is a critical inhibiting factor of its effective use. To raise the status of the facility among the world's best neutron research facilities, it is clear that the HANARO research facility needs strong support from the Korean government for its operation as a national user facility.

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