MULTIPURPOSE UTILISATION OF A MEDIUM FLUX RESEARCH REACTOR – BENEFIT FOR THE SOCIETY

L. ROSTA
Research Institute for Solid State Physics and Optics,
Budapest,
Hungary

Abstract

The Budapest Research Reactor (BRR) was restarted after a major refurbishment and increase in power to 10 MW in 1992. Basically, the experience gained with the utilization of this multipurpose facility during the past 20 years is described here. The utilization aims for 3 major activities: i) Research and development base for the energy sector: scientific and safety support for the Paks NPP; research in energy saving and production. ii) A complex source of irradiations for materials testing and modification, diagnostics in nanotechnologies, engineering, healthcare etc. iii) Neutron beams from the horizontal channels of the reactor serve for exploratory as well as for applied research in a very wide range of disciplines. Graduate and professional training is also in the scope of our activity. The reactor went critical first in 1959. It served nearly 3 decades as a home base for learning nuclear sciences and technologies, to development nuclear energetics, which resulted in launching four power plant blocks in the eighties, as well as to establish neutron beam research in our country. Nearly 20 years passed now that the decision was made — after the falling of the "Iron Curtain" — the practically brand new 10 megawatt reactor should be commissioned and opened for the international user community. The reactor reached its nominal power in May 1993 and neutron beam experiments were available on 4 instruments at that time. Thanks to a continuous development the number of experimental stations now is 15, the research staffs has grown from 10 to nearly 50 scientists and research facilities have been improved considerably. A few important milestones should be mentioned: a liquid hydrogen cold source was installed and the neutron guide system was replaced by a supermirror guide configuration, yielding a factor of 50–80 gain in neutron intensity; a second guide hall was constructed to house a new time-of-flight instrument; BRR became a member of the European neutron scattering network (NMI3). In 2010, the core conversion programme was completed, namely the change of the fuel from high enriched uranium (HEU) to low enriched uranium (LEU) and subsequently a stock of new fuel will ensure the safe operation of BRR for at least a decade to come.

1. INTRODUCTION

Hungary has always devoted particular interest to nuclear sciences. The Hungarian neutron community has made a significant contribution to neutron scattering research for many decades. It is marked by some outstanding achievements of leading scientists like Ferenc Mezei, who invented the neutron spin-echo spectroscopy and the long pulse spallation source concept, László Cser, who was the first to propose and realize neutron techniques for atomic scale holography. Hungary has also been an active participant in the development and formation of ideas for new instrumentation or neutron sources, such as the European Spallation Source (ESS).

The home base for reactor and neutron beam research is the Budapest Research Reactor (BRR) first started in 1959. BRR is one of the leading research infrastructures in Hungary and in Central-Europe. The basic scientific activity at BRR is the use of neutron beam lines for neutron scattering investigations. We have more than 50 years of tradition in this field. BRR is a VVR-type Soviet designed and built reactor: it went critical on March 25, 1959 – with its construction starting in summer 1957.Originally, the reactor power was 2 MW, but it was upgraded to 5 MW in 1967. A second full-scale reactor refurbishment was started in 1986, fully designed and performed by Hungarian companies. The project was supported by the International Atomic Energy Agency (IAEA) and the European Union. The reconstruction was completed by the end of 1990, but due to the political changes in the country, the license for reactor start-up was issued only in 1992. At this time it was decided by the Hungarian Academy of Sciences (the operator of this state-owned facility), that this 10 MW reactor and its experimental stations should be opened for access by the international user community. This opened up a spectacular development both in terms of sciences and economics.

The reactor has been operated by the KFKI Atomic Energy Research Institute (AEKI – one of the research units of the Hungarian Academy of Sciences). In 1992, a consortium, named Budapest Neutron Centre (BNC), was formed as an association of the neutron-research-based laboratories of AEKI and three other academic institutes (RISP – Research Institute for Solid State Physics, IKI – Institute of Isotopes and RMKI – Research Institute for Nuclear and Particle Physics) on the so called KFKI campus site. The role of BNC is to coordinate the reactor utilization and to provide scientific infrastructure for managing access for the international user community [1].

2. THE REACTOR

It is a tank type reactor, moderated and cooled by light water. The area of the reactor hall is approximately 600 m^2. This is extended by a neutron guide hall for the cold neutron instruments (400 m^2) and a second guide hall (120 m^2) was added in 2004 for a thermal beam instrument (TOF).

Until 2009 the reactor was fuelled with Russian type VVR-SM fuel with 36%, uranium enrichment and later due to the program of the core conversion, 20% enriched VVR-M2 type will be used. The core is surrounded by a solid beryllium reflector. The main technical data of the reactor are: thermal power 10 MW; mean power density: 39.7 kW/litre; approx. maximal thermal flux: 2.1 x 1014 n/cm^2s; maximum cooling water outlet temperature: 60^{o}C. The reactor cycle is about 10 effective days, which is followed by a short break for a weekend. The Budapest Research Reactor is known for its reliable operation. 3500-4000 operational hours per year are foreseen for the next years. However, the timetable will be flexible accommodating the various requirements of the instrument developments.

3. CORE CONVERSION

Following the commitment to join the Russian Research Reactor Fuel Return (RRRFR) programme, BRR was prepared to change from HEU to LEU. Under the Bratislava Agreement signed by the presidents of US and Russia in 2004, more than a dozen countries are eligible to receive financial and technical assistance from the US and others to ship their fresh and spent research reactor fuel to Russia for safe and secure management. As an integral part of the RRRFR programme the AEKI signed an agreement with the US Department of Energy in 2005, to repatriate spent and fresh HEU nuclear fuel stored at the BRR site and made a commitment to convert the BRR's core from HEU to LEU fuel.

The first spent nuclear fuel (SNF) shipment was performed in autumn of 2008. This concerned all SNF assemblies irradiated before 2005 The transport logistics was a crucial issue of this back-shipment action, this was the largest amount of spent HEU ever transported: 16 tracks carried the containers of 20 tons each to a railway station in Budapest, then the special rail cargo passed through Hungary and Slovenia to the Adriatic Sea in Koper, where the entire harbour was closed for the transhipment. The special ship took three weeks to travel through the Mediterranean, Atlantic and North Sea to Murmansk, and then the containers reached the final destination in the Ural Mayak by rail again.

According to the RRRFR programme obligation and with the contractual cooperation of IAEA, the back-shipment of the remaining fresh HEU fuel stored at BRR's site was shipped back to Russia in July 2009. According to the core conversion scenario as well as the necessary decay time after fuel removal from the core, a 2nd and final HEU spent fuel shipment is planned in 2014.

The preparation for the core conversion has been running since 2007. The selected type of LEU was the Russian made VVR-M2 fuel: the geometric and thermo-hydraulic parameters are identical, whilst its nuclear features are similar to the previously used VVR-M and -M2 HEU fuel elements. In this way the core conversion scenario was including HEU and LEU fuels with gradually decreasing HEU fuel assembly numbers. During the core conversion 4 cycles with mixed HEU-LEU cores will take place (over 8 months), then the utilisation of HEU fuel will be finished in early 2012 and later on only 20% enriched fuel will be used. According to neutronics calculations no more than a 10% loss in neutron flux is expected due to the core conversion [2].

4. MISSION OF THE REACTOR—MULTIPURPOSE UTILISATION

The Budapest Research Reactor has been utilized as a neutron source for basic and applied research or direct applications in various fields of industry, healthcare as well as in exploration and conservation for objects of cultural heritage. The major fields of the reactor utilization are as follows:

i) BRR is a research and development base for the energy sector. In Hungary 40% of electric energy is produced by the Paks Nuclear Power Plant (4 blocks of 500 MW electric power). The expertise and knowledge accumulated at BRR during the past decades is a solid basis for scientific and safety support for the Paks NPP as well as for the national nuclear regulatory body. BBR also serves as a scientific and development tool in other fields of energy research, both in energy saving and production (e.g. development of new materials for energy production and storage, research of materials and structural components for fusion energy or reactors of new generation, development of new energy saving technologies such as superconductors).

ii) This reactor is also a complex source of irradiations for materials testing and modification, diagnostics in nanotechnologies, engineering, healthcare etc. The radioisotope production – using vertical irradiation channels of the core – is crucial for society. For example, in our country 60 hospitals are supplied by isotopes produced at BRR and nearly 5% of the population is involved in the usage of isotopes mostly for diagnostics but also for therapy. A fast rabbit system serves as a pneumatic irradiation facility, situated in the reactor core; it provides convenient production of short-lived isotopes as well as neutron activation analysis for environmental chemistry, geochemistry, biological and medical research. BAGIRA is the name of a gas-cooled irradiation rig in a dry channel inside the core. This serves basically for irradiation of nuclear reactor vessel and fusion equipment materials to investigate irradiation ageing. This is complemented by a laboratory equipped for hot sample studies.

iii) The most extended utilization of BRR is neutron beam research. This activity results in a significant number of experiments (including PhD and contract-based works). For example in 2010, about 100 experiments were completed by local staff and in collaboration with national or foreign users coming from university, industrial or other research laboratories. The number of publications (typically quoted in annual reports) is 100-120 a year. BNC is a recognized component of the European network of neutron centres and a partner in the EU Framework Programme projects. It was a great honour at the closing meeting of the last framework programme’s NMI3 in 2009 that out of nearly 1000 experiments performed under the umbrella of the programme, 32 highlights were presented by four European experts and 11 of these highlights were coming from BNC. This shows that our users, coming mostly from developing regions, produce many exciting ideas and experiments although the quality of our facilities can do with further development.

iv) University education as well as postgraduate and professional training in the nuclear field has always been an important task at BNC. The first international neutron scattering school was organised in 1999 together with the 2nd European Conference on Neutron Scattering in Budapest (this was an occasion for several hundreds of neutron scientists to visit BRR). It has developed into a series of regional events. For example, the 5th Central European Training School (CETS) was held at BNC in June 2010. These schools provide an introduction to neutron scattering with special emphasis to hands-on-training at BRR facilities. Regular courses of 4-6 weeks length are organised for training of scientists coming from developing countries with special emphases on topical/instrumental purposes e.g. in neutron reflectometry or strain scanning.

5. NEUTRON BEAM RESEARCH

For neutron beam measurements different types of horizontal channels are available: six radial thermal, two fast neutron channels and two tangential beam tubes. A 15x27 m2 guide hall extending from the reactor hall, housing three neutron guides, was constructed in 1990. In 2000 a liquid hydrogen cold neutron source (CNS) was built and installed [3]. The construction of the CNS has been followed by the replacement of the obsolete neutron guides by a new supermirror guide system both for the in-pile and out-of pile part. The instrument development programme is continued and currently 15 experimental stations are in operation (Fig.1). BRR is a recognized component of the European network of neutron centres. The number of experiments (including PhD and contract-based works) is 120-150, the number of publications (typically quoted in annual reports) is 100-120. Industrial and medical applications (e.g. radioisotope production, scientific instrument production) provide important economic benefit. For example, the yearly turnover of industrial companies related to the utilization of the reactor exceeds about 3 times of the reactor operating costs.

6. HIGHLIGHTS FROM THE NEUTRON RESEARCH ACTIVITY

The main field of activity at BNC is condensed matter research, nuclear spectroscopy, nuclear analytical chemistry as well as applied research (e.g. engineering, geology, energy, archaeometry). Some typical examples of research highlights are described in the following section.

— The principle and two ways of experimental realisation of atomic resolution neutron ***holography*** was proposed by L. Cser and has performed the first successful experiment (on D9 diffractometer at the ILL) proving the feasibility of the so called internal detector concept on a Pb-Cd single crystal (Fig.2). Neutron holography is a unique method for direct measurement of local lattice distortions with sub-picometer accuracy [4]. At BRR holographic spectra are recorded routinely on various crystals (Fig.3).

— ***Small angle neutron scattering*** (SANS) study of the nanoscale defect structure in Al-alloy pistons at different stages of usage with anisotropic distribution and highly geometry dependent growth of precipitates was revealed. This study lead to a substantial increase of life-time of the engine [5].

— Production of counterfeits or imitations is almost coeval with production of original and valuable art objects, but thanks to analytical tools applied to objects of ***cultural heritage***, identification of fakes is possible based on some significant compositional or structural features. Lapis lazuli, a beautiful stone of light-blue colour was a high-graded gemstone and pigment in the Near-East, in Egypt, and later in Europe (Fig). Its geological occurrences are well known and show smaller or greater differences in chemical composition [6]. Already in antic times, and later on there were attempts to produce ‘artificial’ lapis lazuli, such as ‘Egyptian Blue’, i.e. CaCuSi4O10. We found that both PGAA and TOF-ND are capable to distinguish between ‘false’ and ‘true’ lapis lazuli. In fact, ‘Egyptian Blue’ is easy to distinguish from lapis lazuli by PGAA, since the first contains significantly high amount of Cu. Similarly, diffraction patterns of ‘Egyptian Blue’ and real lapis lazuli are different. On the other hand, neither PGAA, nor TOF-ND did show significant difference in the composition of real lapis lazuli and supposed ‘fake’ lapis lazuli.

Figure 1. Layout of the horizontal neutron beam facilities at the Budapest Research Reactor.

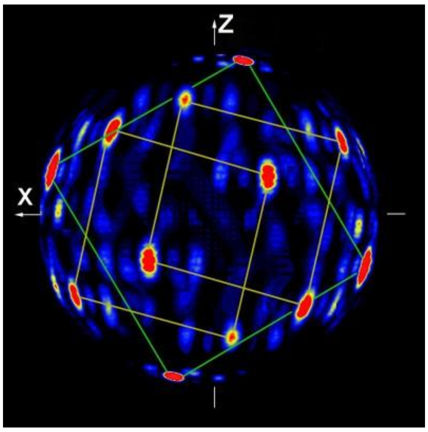

Fig. 2. 3D holographic image of the 12 Pb atoms surrounding the Cd atom on a sphere of a 0.35 nm.

Fig. 3. At BRR a dedicated holography instrument is in operation.

Fig.4. The Formula 1 racing car and its Al-alloy piston studied by SANS

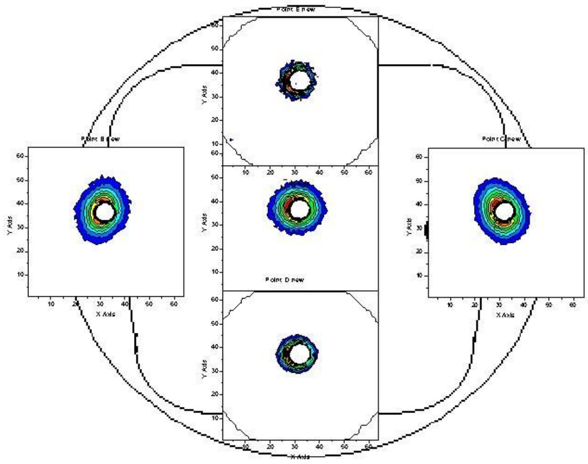

Fig.5. Top view of the piston with 2D SANS images at various points with anisotropic precipitate structure

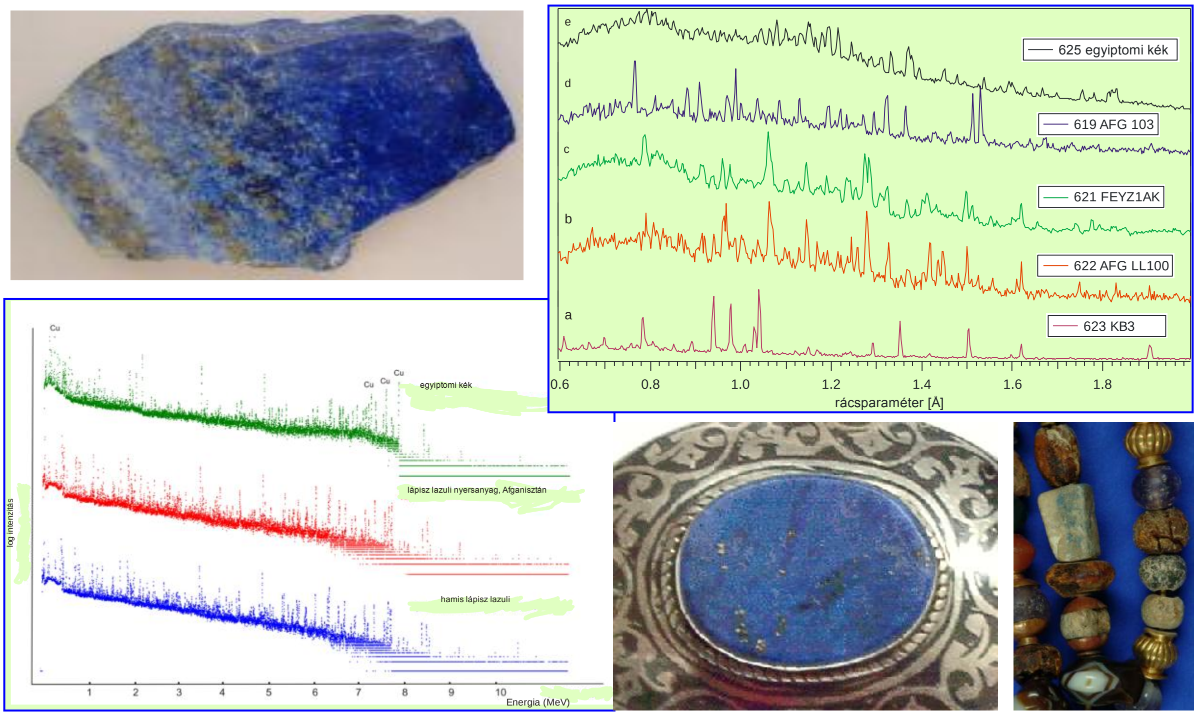

Fig.6. Lapis lazuli stone (upper left) and insertions in jewels. Prompt gamma activation analysis spectra (left) and neutron diffraction patterns of stones of different origin

Research of neutron techniques and development of instrumentation were always in the scope of our activities. A new technique we developed some years ago is getting now wide application in neutron moderator or beam transport characterisation. Neutron beam phase space mapping by energy resolved pinhole imaging requires four major components: pinhole camera neutron optics, TOF spectral analysis, high performance 2D-detection system and a proper software for ***x-y*** and ***t*** imaging pinhole camera neutron optics [7]. The principle of the imaging technique is shown in Fig.7 (upper left) and a measured by the 2D detector image of the cold neutron moderator bightness passed in a neutron guide section is presented in the insert of the right upper figure. a,b, c – are the spectral distribution curves corresponding to detected flux distribution, spectrum corrected for detector gas absorption efficiency and Maxwell-Boltzmann fit, respectively. The marked bright spot is chosen in this way as a source for a focusing device. The bottom pictures show such devices (detector and guide) which were used in this experiment. These devices are fabricated by spin-off companies we are working together with for development and technology transfer.

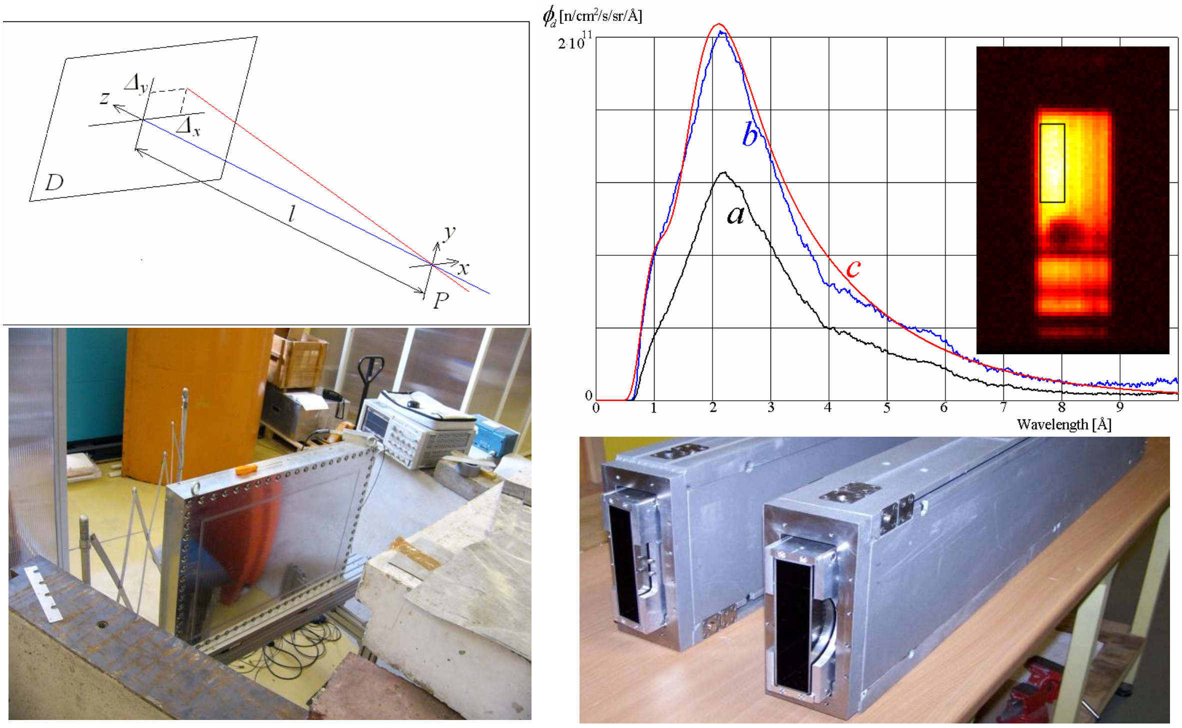

Fig.7. The scheme for phase space imaging, measured spectra and below: testing of a 2D multiwire chamber detector (left) and neutron guides developed and fabricated at our site

7. DEVELOPMENT OF REACTOR UTILISATION IN FIGURES

Table 1. gives some figures related to the development of some parameters relevant to the scientific use of BRR. Table 2. shows some figures related to finances (figures are given in Hungarian Forint – the rate is ~250 HUF/€).

Table 1.

Year	Employment related to operation and utilisation	Neutron researchers at BRR site	Neutron researchers total Hungarian	Number of experimental stations	Number of beam-days	Number of publications
1993	70	18	40	4	120	30
1996	100	55	69	6	800	50
2004	227	91	176	11	1235	120
2010	244	100	180	15	1800	125

Table 2.

Year	Reactor operation costs	Cumulated value of research grants	Direct income of the reactor	Turnover of reactor related companies
1993	15	5	0	5
1996	80	90	5	15
2004	300	1200	45	600
2010	650	2500	80	1200

8. REGIONAL ROLE AND PERSPECTIVES

We consider that with the current set of instruments BNC has nearly reached its maximum of beam-line/operation/man-power capacity. In the near future the improvement of the quality of experiments, sample environment, reliability of instruments is in the scope of development, rather then installation of new facilities. We believe that BNC's role is to provide opportunity for neutron research in the Central-European region where around 800 potential neutron users are present (ENSA survey). BRR in the present form started its operation in 1993 and it had been designed for 30 years. Technically, the reactor can be operated until 2023 and even beyond. We are convinced that our reactor is ready to fulfil its traditional mission duties; it is however, obvious that BNC should be adapted to the changing world requirements. Europe has started to construct powerful new infrastructures intended to serve the needs of the entire continent in various fields of R&D by dedicated facilities: ESS in Lund, Sweden, Jules Horovitz Reactor in France, High Flux Isotope Reactor in Petten, the Netherlands. These are a few of the major specialised nuclear facilities to be built by 2015-2020, that will take over or extend the traditional roles of the present multipurpose research reactors. The activity of existing reactors, including BRR, is important in the transition period, i.e. at least up to ~2023. Moreover, the Budapest reactor and other regional research and training reactors will offer improved services for the user communities, which need to be trained and prepared for the utilisation of the new cutting-edge European facilities when they become operational.

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