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Meeting Report of

the IAEA Technical Meeting

on

Commercial Products and Services of Research Reactors

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International Atomic Energy Agency

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1. BACKGROUND AND OBJECTIVES

1.1. Background

In June 2010 according to the IAEA Research Reactor Database, from more than 670 research reactors (RRs), including critical facilities, constructed around the world, 234 were still operating and 6 were under construction or planned, while 14 more were under the status of "temporarily shut down". Of the RRs that are no longer operating, some have plans to resume operation in the future, some are undergoing decommissioning or waiting to be decommissioned, but others are in an extended shutdown state with no clear plans for their future. Although the number of RRs is steadily decreasing, more than half of the operational RRs are still heavily underutilized, and in most cases, underfunded. In order to continue to play a key role in the further development of peaceful uses of nuclear technology, the decreasing and rather old fleet of RRs needs to ensure the provision of useful services to the community, in some cases with adequate revenue generation for reliable, safe and secure facility management and operations. In a context of declining governmental financial support and needs for improvement of physical security and conversion to LEU fuel, many RRs are challenged to generate income to offset increasing operational costs.

Underutilized RRs lack the financial resources needed to improve or upgrade the facility to the conditions demanded by potential users and customers, which creates a significant obstacle to increasing utilization and therefore additional revenue generation. Many RRs have limited access to potential customers for their services and are not familiar with the business planning concepts needed to secure additional commercial revenues or international program funding. This not only results in reduced income for the facilities involved, but sometimes also in RRs services priced below full cost, preventing the recovery of back-end costs and, furthermore, creating unsustainable market norms. Although the international RR community possesses the expertise to address these concerns, this knowledge is not uniformly available. Parochial attitudes and competitive behaviour restrict information sharing, dissemination of good practices and mutual support that could otherwise result in a coordinated approach to market development built upon the strengths of facilities. These attitudes are based, in part, on the belief that the markets for RR products and services are "zero-sum," with market gains by one RR resulting in losses to other "competing" reactors. However, the success of user groups and organizations such as WANO in the nuclear power generation sector show that the benefits of cooperation can be obtained without sacrificing commercial interests.

Renewed interest in nuclear power, and therefore, in nuclear education and training, the worldwide expansion of diagnostic and therapeutic nuclear medicine and the extensive use of semiconductors in electronics and other areas present new opportunities for RRs, prominently among them, markets for products and services in regions and countries without such facilities. It is clear that such initiatives towards a greater self-reliance will need to address and consider such aspects as market surveys, marketing plans, business plans and cost of delivery services. At the same time, the present and future potential end users of RR services should be better informed about the capabilities and products RR can provide.

1.2. Objectives

The technical meeting will provide a forum to exchange good practices, practical experiences and other relevant information through scientific presentations and brainstorming discussions, leading to the following overall objectives:

- Promotion and development of commercial applications of RRs
- Enhancement of RR utilization in Member States for practical applications
- Strengthened regional and international cooperation between RR centres from developing and developed countries with special emphasis on the transfer of knowledge and good practices

The technical meeting will focus on the present status and future potential for commercial applications of RRs. The following areas are of high priority:

- Nuclear education and training
- Production of medical and industrial radioisotopes
- Irradiation services for neutron transmutation doping (NTD) of Si, gem coloration, tests of electronic devices, food and goods sterilization, etc.
- Analytical techniques such as instrumental neutron activation analysis (INAA), prompt gamma neutron activation analysis (PGNAA), delayed neutron counting (DNC), fission track dating, etc., with emphasis on complementary services when compared to non RR based methods
- Neutron beam techniques such as neutron imaging, small angle neutron scattering (SANS), neutron diffraction, etc.
- Support of R&D relevant to present nuclear power reactors (e.g., ageing management, development and qualification of new fuels, etc.)
- Support of R&D relevant to future advanced nuclear systems, both fission and fusion reactors (e.g., development and qualification of fuel and structure materials, reactor design and licensing, validation of modelling tools, nuclear data provision, etc.)
- Other potentially revenue generating applications

2. WORK DONE DURING THE MEETING

The meeting was attended by 30 participants, from 23 Member States. The meeting started off with welcome, opening and introductory remarks by the IAEA senior management representatives from the Division of Physical and Chemical Sciences, Department of Nuclear Sciences and Applications, and the Division of Nuclear Fuel Cycle and Waste Technology, Department of Nuclear Energy (see attached Agenda in Annex I). Later the welcome address was given by Mr D. Ridikas, the IAEA Scientific Secretary of the meeting. The self presentation of all meeting participants followed afterwards. Mr B. Ponsard (SCK*CEN Mol, Belgium) was nominated as a chair person and Ms G. Hampel (University of Mainz, Germany) was appointed as a *rapporteur* of the meeting. Right after followed a brief presentation by Mr D. Ridikas, the IAEA Scientific Secretary, on specific objectives of the meeting within the ongoing IAEA project D2.01 on Enhancement of Utilization and Applications of Research Reactors.

2.1. Summaries of individual presentations

Later the meeting continued with individual presentations, which can be grouped into the following main categories:

1. Education and training
2. Radioisotope production
3. Silicon doping
4. Neutron activation analysis
5. Neutron beam applications
6. Irradiations of materials/fuels
7. Other applications of RRs

Book of abstracts for all presented papers is given in Annex II, where brief statement on each contribution covers major contents only. The abstracts are given according to the presentation order. Copies of all presentations, papers and administrative information were distributed at the end of the meeting to all participants and may be obtained from the Scientific Secretary on request.

3. RESULTS OBTAINED

All presentations were followed by adequate time for discussions/questions, widely used by the participants and chairs. Further, intermediate summaries and compilations of findings and comments contributed to involving participants into the aims of the meeting and the strengthening of the exchange of knowledge and experience. The following text resumes the outcome of the discussions, observations and intermediate conclusions relevant to the seven main topics indicated in the previous section. The below Tables, taken from the IAEA TECDOC-1234 (2001), remains a useful guidance to associate various applications to the RR power.

Power Level	Education & Training	NAA	Isotope Production	Geochronology		Neutron Radiography (2)
				K/Ar	Fission Track (1)	
30 kW	X	x	x			
250 kW	X	x	x			X
1 MW	X	X	x	x	x	X
2 MW	X	X	X	x	X	X
>=10 MW	X	X	X	X	X	X

Power Level	Transmutation Effects			Testing		Material Structure Studies (2)	PGNAA (2)	Positron Source (2)	NCT (1 or 2)
	Silicon Doping	Materials Irradiation	Gemstone Coloration	Instr. & Calib.	Nuclear Fuels (3)				
30 kW				x					
250 kW				X					x
1 MW	x	x	x	X		x	x	x	X
2 MW	x	X	X	X		X	X	X	X
>=10 MW	X	X	X	X	X	X	X	X	X

x - Some capability
X - Full capability
(1) Requires a thermal column.
(2) Requires a beam tube.
(3) Requires a loop or special irradiation facility.

3.1. Education and Training

Nuclear education and training is one of the most important tasks of low power RRs. These reactors offer a large variety of possible experiments both in academic and practical areas, ensure an easy access, and can be run at low operational costs. In particular, countries managing nuclear power programmes have a special need to use low power RRs for training their future staff on various technical levels, both from operational and regulatory organizations. Furthermore, this is applicable not only for emerging nuclear countries but also for countries with long term nuclear programmes, as senior staff retires and the past decades have showed a lack of interest from new generation in the nuclear field. Therefore a gap between demand and supply of well trained nuclear staff is now more than evident. RRs are expected to play the major role to fill this gap. A number of individual presentations documented these needs. It was also emphasized that there is a great opportunity for small RRs to be more effectively used not only for standard training courses within the academic field but also for offering commercial training services to other groups such as nuclear industries, governmental institutions, hospitals, etc. Both national and regional markets should be explored in this regard. It was also agreed that nuclear simulators available at most of the NPPs cannot fully replace the hands-on training at RRs. As a result, a number of small RRs still have to extend the existing training courses, both in scope and capacity of trainees to be trained, in order to respond the increasing demand from nuclear power industries, where nuclear safety and nuclear security aspects for the course curricula should be developed accordingly. RRs involved in design and organization of such courses should seek for closer collaboration and formation of networks in order to unify the curricula, share knowledge/experience and facilities regarding different capabilities.

The following are the desirable features for nuclear reactors for training purposes:

- High degree of safety: safety is, of course, an overriding requirement in training devices, especially in RRs
- Ease of operation: training reactors should be designed so that a minimum number of restrictions are imposed on the students and instructors (e.g. the control console can be operated safely by inexperienced students after a short instruction time).
- Ease of maintenance: equipment should be arranged to provide easy access for maintenance, and components should be selected for life and minimum maintenance.
- Ease of experiments for students and instructor: for training reactors, ease of a wide variety of training and research experiments for students are highly desirable.

Note: 1000 is an approximate number of professional staff to be trained at different level of areas/competence per new NPP to be built and operated. Typical training fee at the RR can be from USD 5,000 to 10,000 per person for 10 days training course.

3.2. Radioisotope production

Radioisotope production for industrial (radiography, process evaluation, etc.) and medical (diagnosis, therapy, palliation, etc.) applications remains one of the most important commercial applications of RRs, in particular in the case of dedicated large-scale production facilities thanks to the availability of high neutron fluxes and dedicated irradiation channels. The isotope production programme involves several interrelated activities such as target fabrication, irradiation in RR or accelerator, transportation of irradiated target to radioactive laboratory, radiochemical processing or encapsulation in sealed source, quality control and transportation to end users. Each step needs experts from respective disciplines, laboratory facilities equipped for radioactivity handling and other supporting infrastructure.

Radioisotopes are produced in a RR by exposing suitable target materials to the neutron flux for an appropriate time. Most of the reactor-produced radioisotopes, are products of the (n,gamma) reaction as ^{60}Co, ^{192}Ir, ^{89}Sr, ^{153}Sm, ^{186}Re, ... This reaction is also referred to as radiative capture and is primarily a thermal neutron reaction. In some cases the absorption of neutron leads to emission of a charged particle. Such a reaction is termed as (n,p) or (n,alpha) reaction, caused by fast neutrons having energy more than a particular value known as threshold energy (production of ^{67}Cu, ^{58}Co, …). Finally, thermal neutron induced fission of ^{235}U provides a host of useful radioisotopes, as ^{131}I, ^{133}Xe and ^{99}Mo (for the manufacture of ^{99}Mo/^{99m}Tc generators). ^{99m}Tc as a decay product of ^{99}Mo is a crucial radioisotope which is used in about 80% of the diagnostic nuclear imaging procedures in nuclear medicine.

Factors that determine the type of nuclear reaction taking place and the rate of production of the product are:

– energy of the neutrons
– neutron flux
– irradiation time
– characteristics of the target material

– reaction cross-section for the desired product.

Some isotope production is possible in a low ($<10^{13}$ cm^{-2} s^{-1}) flux reactor. However, more is possible in an intermediate (10^{13}–10^{14} cm^{-2} s^{-1}), high ($>10^{14}$ cm^{-2} s^{-1}) or very high ($>10^{15}$ cm^{-2} s^{-1}) flux reactor. It should be recognized that in order to be able to realistically produce radioisotopes, the operating cycle of the reactor needs to be as long as possible, i.e. several weeks.

There is certainly dedicated niche for low power research reactors to produce short-lived radionuclides such as ^{56}Mn, ^{18}F, ^{24}Na, ^{42}K, ^{82}Br, ^{116m}In, or ^{128}I not generally available by shipment from abroad but of considerable use in demonstration, in teaching and in research. The use of short-lived nuclides due to their fast decay produced by a reactor on the spot is particularly suitable for teaching purposes because of their inherent safety. The preparation of radioisotope calibration sources for a variety of applications in radiation analysis, instrumentation development and calibration, is only possible when produced locally.

A gamma spectroscopy system is needed for quality assurance purposes to provide reliable measurements of radioactivity levels and purity. Indeed a complete quality assurance (QA) programme must be in place for any commercial work in this field. There are some significant issues relating to safety analysis, and licensing that must be addressed prior to radioisotope production. It should be determined that possible abnormal occurrences during the production process are within the bounds of the reactor design basis and the operational limits and conditions. In addition, the use of radioisotopes requires licensing by a competent authority.

While some start up costs may be absorbed by the operating organization, cost recovery for production and distribution should be the goal.

Note: Present world market of ^{99}Mo is of the order of 12,000 "6-day Curies per week"[1] with the irradiation costs ranging from USD 60 (current situation) to USD 600 (economically sustainable)[2] per Curie.

3.3. Neutron transmutation doping of silicon

The neutron transmutation doping (NTD) of silicon is another commercially attractive application of RRs. The basic material for the semiconductor industry is silicon, doped with small quantities of other atoms (e.g. phosphorous) in order to provide the semiconductor characteristics. The NTD provides the highest quality in doping uniformity (e.g. for power electronics). The NTD is based on the transmutation of ^{30}Si into ^{31}P by thermal neutrons following the reaction $^{30}Si(n,gamma)^{31}Si$ and beta decay to ^{31}P. ^{30}Si has an isotropic abundance of 3.1% in natural silicon.

A RR aiming to offer the service of Si doping need to provide one or more irradiation rigs able to process ingots with different diameters. The primary business today is based on ingot diameters of 127 mm (5 inches) and 152 mm (6 inches), and the demand for the irradiation of ingots with a diameter of 203 mm (8 inches) is noticeable but not yet dominant. Due to increasing self shielding within the Si samples, it is not yet clear if the processing of Si exhibiting even larger diameters will be requested in future. Corresponding test irradiations are underway at present (e.g. Japan). The minimum acceptable

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[1] These are '6-day curies', meaning they are the number of curies six days after the end of the production process, which is generally eight days after irradiation in the reactor is completed.

[2] "*The Supply of Medical Radioisotopes: An Economic Study of the Molybdenum-99 Supply Chain*", NEA/OECD No 6967 (2010).

height of the irradiation stack, which typically is made up of at least 2 ingots, must be greater than 300 mm. Besides rotation of the ingots during irradiation, a reliable technique to provide a sufficiently uniform neutron flux density along the central axis of the ingot, is crucial. The optimum thermal neutron flux density in the irradiation position is between 5×10^{12} and 5×10^{13} cm^{-2} s^{-1}; in particular for Si with a high target resistivity of at least 200 Ω·cm, a high Cd ratio within the irradiation position is desirable. It is important to mention that in addition to the irradiation equipped RR facility, the irradiated Si storage area for at least of 1 t of Si, devices for cleaning of irradiated Si and instruments and trained staff for the performance of sensitive release measurements according to radioprotection regulations are absolutely necessary.

Note: The annual capacity of a typical High Flux Reactor doping facility is between 10 to 15 tons per year. It is estimated that worldwide approximately 120-150 tons of silicon single crystals are doped in research reactors every year with the irradiation cost of the order USD 70-100 per kg.

3.4. Neutron Activation Analysis

Neutron Activation Analysis (NAA) is a qualitative and quantitative analytical technique for the determination of (trace) elements in a variety of complex sample matrices. NAA is the most simple and the most widely used application of RR. Almost any reactor of a few tens of kilowatts and a neutron flux of at least $1x10^{11}$ $cm^{-2}{\cdot}s^{-1}$, as well as high flux reactors, can be used for NAA. In addition, many of the uses of trace element identification can be directly linked to potential economic or social benefits. Therefore, NAA is a one of main applications of RR in a commercial point view, but it also can have a significant contribution to the social justification of the facility. The characteristics of the NAA technique can be summarized as follows:

- Non-destructive analysis (Instrumental NAA)
- No influence of the chemical binding (no chemical matrix effects)
- Multi-element determinations
- Low detection limits for 30–40 elements
- The use of radiochemical separation to overcome interferences in complex gamma-ray spectra (Radiochemical NAA)
- An inherent capability for high levels of accuracy (trueness and precision) as compared to other trace element analysis techniques.

The main advantages of NAA over other analytical techniques (such as ICPMS) are:

- Little sample preparation, thereby minimizing the possibility for contamination
- Adequate sensitivity for most elements
- A relatively rapid analysis with turnaround times of only a few days.
- Physical principles and independent method validation.

Due to its inherent sensitivity and degree of accuracy, NAA has been extensively applied to environmental sciences, nutritional studies, health related studies, geological and geochemical sciences, material sciences, archaeological studies, forensic studies, etc. In addition, NAA has a role in the metrology for chemical analysis e.g. in the characterization of matrix reference materials. Besides the well-known typical relative (comparator) method, the k_0-standardization method is now used as useful tool for INAA application, especially for multi-element determinations.

In brief, NAA with various combined techniques such as INAA, RNAA and DNC (Delayed Neutron Counting) can be applied to the following areas:

1) Mineral characterization and in geological sciences: irradiation of mining samples to detect metal traces with high trueness and precision, which is useful for identifying veins in metal mining and in surveys; to determine the abundance of elements in different areas; to analyze rocks and minerals; to quantify impurities in crude oil (“online” method); etc.

2) Archaeology and fine arts: The accurate knowledge of the composition of an antique object is vital for many social sciences. Trace detection allows for the dating of objects and also provides information on the place these objects were manufactured. The most significant applications correspond to the analysis of ceramics and pottery objects, glass, obsidian and marble objects, old coins and metallurgic objects, as well as the dating and origin of paintings and structural painting studies.

3) Environmental pollution control: NAA contributes to the control of atmospheric pollution by the identification and determination of pollutants in addition to studies on the dispersion and origin of these atmospheric pollutants. It can also provide the capability to identify microelements contained in soil, river, water and sea bed sand and environmental and foodstuff samples, etc.

4) In biology and medicine: the determination of trace elements in different human tissues both normal and with pathologies for research, diagnose and therapy purposes; kinetic studies on metabolisms and element distribution in the human body, for which it is important not only to determine the concentration of the element but also its exchange speed among different organs.

5) Heavy industry metal characterization and material sciences: NAA is significant in the quality assurance process within heavy industry, since heavy material samples are analyzed to identify isotope concentrations, guarantee their origin and verify the effect of impurities on their properties. It is applied to determine impurities and higher elements, to quantify oxygen in steels and metals; to analyze impurities in materials of reactor in-core components, etc.

6) Forensic science is another important area of application of NAA.

Some specific remarks on Delayed Neutron Counting
The Delayed Neutron Counting (DNC) facility is used to determine the natural Uranium content in uranium ore samples supplied by mining companies. A typical facility consists of a shielded counting chamber with five Boron Trifluoride detectors to measure neutrons consisting of ore samples irradiated at a flux of approximately $5x10^{12}$ cm^{-2} s^{-1} for one minute. The neutron count data are automatically input into a computer program which calculates the natural uranium content in the sample. DNC is particularly useful in determining if a specific site is suitable for mineral exploration. Therefore, this technique can easily be expanded for commercial use.

Some specific remarks on PGNAA
PGNAA utilizes prompt gamma rays produced following neutron capture in a specimen, which may be a solid or a fluid. The technique has applications in geological, atmospheric, medical and environmental fields. A PGNAA facility requires a thermal or cold neutron beam, an irradiation position and a Ge-detector connected to a MCA/computer system to analyze the measured spectra of gamma rays. The collimated neutron beam should preferably be at least 10^{8} cm^{-2} s^{-1}, have a (very) low gamma background (hence a preference to use a tangential beam line), with a cross-section of a few cm^2. Typical examples include the detection of boron in blood and tissue samples of patients when requested by the Boron Neutron Capture Therapy (BNCT) and the detection of pollutants in air filters for environmental purposes.

In case of commercialization of the NAA, one should keep in mind the following three issues: a) infrastructure improvement through implementation of automation in all phases including sample irradiation, sample measurement, data acquisition, quality control, etc., b) skills improvement of the involved personnel, c) constant interaction and established collaboration with customers.

Note 1: One should make sure be able to irradiate and analyze from 2000 to 3000 samples per year to start generating substantial income, although this would be true only if the RR operational costs are relatively small. Typical revenues are from USD 50 to 300 per analyzed sample.

3.5. Neutron beam applications

Non Destructive Testing (NDT) by neutrons is commonly used to improve the knowledge of materials structures and defects in materials or different objects. Perhaps the most known technique is the neutron radiography being similar to X-ray analysis but using neutrons. In the past, the "picture" used to be registered on a neutron sensitive foil (Gd, Dy) which activates a film by photons produced in a converter foil via neutron interaction. In the past few years, several techniques in digital imaging were successfully performed providing high sensitivity detectors with important performances regarding their dynamic range and linearity. This holds mainly for imaging plates and detectors based on CCD-cameras with a scintillator screen as primary neutron-to-light converter. Other methods are not yet completely optimised for neutron imaging (amorphous silicon arrays, micro-strip gas counters), but have a high potential as detectors in radiography and in neutron scattering experiments as well. Recorded 2D images are reconstructed using sophisticated image reconstruction software, leading to 3D information of the inspected object/sample – basis for the computed neutron tomography. Present applications are corrosion studies in aluminium (aircraft industry), behaviour of moisture in building materials, distribution of hydrogen, oil and or lubricants in mechanical equipment, including fuel cells and car engines.

3.5.1. Neutron Radiography and Tomography

Neutron radiography is even possible at low flux reactors. Due to the strongly different interaction mechanisms of neutrons and X-rays with matter, neutron tomography can reveal totally different structural characteristics of an industrial component. Where X-rays easily penetrate polymers or glue and are strongly absorbed by metals, neutrons are more strongly scattered by hydrogen containing phases as compared to the metal parts. With a stronger neutron flux available at medium and high flux reactors, neutron tomography offering spatial resolution down to 50 µm becomes feasible. Additionally, contrast enhancements based on the application of a monochromatic neutron beam (e.g., Bragg edges) have been successfully demonstrated.

3.5.2. Small Angle Neutron Scattering

For medium and high flux reactors equipped with a cold neutron source, small angle neutron scattering can have a strong impact by providing a service revealing statistical material characteristics on the nanometer scale, like size distributions and orientation parameters of pores and precipitations. There are few facilities around the world where SANS instruments are funded and operated directly by industry.

3.5.3. Neutron Diffraction for Residual Stress and Texture Analysis

For medium flux reactors, providing a neutron scattering option for residual stress and texture analysis as a service for industry is clearly feasible. Neutron diffraction based residual stress determination is the only quantitative method to evaluate the averaged 3-dimensional strain tensor within the sampling volume defined by the instrumental setup. The determination of residual stress states within the volume of an industrial component is of special interest during the optimization phase of production processes, sample design and for failure analyses purposes. Neutrons can deliver the reference data for validation of materials models and for calibration of conventional NDT tools. This results in an enhanced reliability of lifetime predictions, enabling less conservative quality control decisions without reducing the degree of safety. Finally the appropriate use of neutrons as a reference method can be really cost-effective for commercial users.

The following has been highlighted as an important conclusion under this topic:

a) In order to enable fast and accurate neutron beam measurements, it has to be recommended to provide at least one dedicated materials science instrument. Each research team should look for a dedicated niche, where specific neutron beam applications could be developed and promoted

b) In order to optimize the instrumentation according to the needs of the market, a broad interface with the end users is needed. Therefore close cooperation with the engineering community with a special focus on non-destructive testing and structural integrity would potentially yield strong benefits.

3.6. Material & Fuel irradiations

Material testing is mainly linked to power generating applications of nuclear energy, with some activities oriented to the testing of materials used in material test reactors (MTRs). During the meeting material irradiations were presented as performed at the BR2, HANARO, JMTR, CARR, INR-TRIGA and Dhruva reactors, constituting a major activity, though minor activities are also being developed at the IRT-2000 and OPAL reactors. In general, material irradiation programmes are closely linked to the support and development of national and, to a lesser extent, international nuclear power generation industries. The primary goal is to support currently operational reactors or reactors under construction, with projects towards the development of emerging future generation reactors (GEN IV reactors). Support to current generation reactor operation and deployment results in programmes addressing irradiation damage in structural materials for ageing management (safety analysis and life extension) and fuel irradiations to enhance fuel cycle economy and safety. The main advantage in the use of research reactors lies in their potential to provide “accelerated” irradiations for ageing management, well controlled and instrumented in-pile test conditions and the potential for pre-commercial irradiations to support licensing of evolutionary fuel utilization. Irradiation programmes in support of current generation reactors have a more or less repetitive and standardized character.

In this context the following issues were identified as important:

- The development of material irradiation and testing procedure in order to validate the relevance of the material irradiation condition in the test reactor towards the power reactor condition
- The construction and safe operation of fuel test loops, simulating the thermal hydraulic core conditions in power reactors
- The availability of the facilities irradiation and post irradiation examination facilities on the same location or the construction of an international network.

RRs also play an important role in the development of new generations of reactors by performing test irradiations of materials and, to a more limited extent, fuels. These efforts require also the development of specific irradiation devices, as these irradiations are less 'standardized' and more challenging as irradiations of materials for current generation reactors. Enhancement of international accessibility and utilization in order to avoid unnecessary duplication and increase complementary studies among research reactors was strongly recommended by the meeting participants.

The following areas summarize RR support to commercial power reactors, and therefore potential contract-based revenue generation:

- Reactor safety analysis
- Extension of reactor life time
- Improvement of fuel performance
- Development and validation of fuel
- R&D on nuclear materials, improvement of materials, development of new cladding materials
- Development of new reactor techniques and advanced instrumentation techniques
- R&D together with the nuclear power reactors
- Irradiation tests of reactor materials, high temperature irradiation tests

3.7. Other potentially commercial applications of RRs

3.7.1. Gem Coloration

There is an opportunity to use RRs to enhance the quality of and, thus, add value to, gemstones. A few gemstones such as topaz, diamond, etc., can reach 30 times their natural value thanks to neutron irradiation. A combination of gamma radiation and high energy electrons with neutron irradiation can increase the values of more variety of gems. The application requires substantial R&D and experience prior to commercialization. For safety aspects, each irradiated grain product should contain a radiation residue less than the acceptable value of 2 nCi/g. **State regulation related to gemstone irradiation varies from country to country, and some countries like the EU do not allow commercialization of irradiated gem stones at all.**

3.7.2. Medical applications

Unlike higher powered RRs, low power reactors cannot produce routinely radionuclides important in radiopharmacy. However, recently in several RRs a Boron Neutron Capture Therapy (BNCT) facility for brain tumour treatment has been installed. Especially reactors in the 100 kW to 1 MW range have been adapted for this task (e.g. Mushashi Institute in Japan, VTT TRIGA in Finland, and MIT in USA). A large amount of work has recently been put into developing new Boron compounds for BNCT as well as into optimization for neutron spectrum shifters to optimize the neutron energy during irradiation. In addition, high flux reactors such as HFR Petten (Netherlands), FRM-II in Munich (Germany) and some RRs in Russia, Argentina and China have also developed or designed such trial treatment facilities.

In brief, the BNCT is a specific tumour therapy using secondary (high LET) radiation which in principle destroys the tumour without causing collateral damage. BNCT is currently applied for the treatment of certain type of tumours like head and neck cancers, melanoma and glioblastoma. For example, currently, 1-2 patients per week are treated at the Finnish TRIGA RR. Italy, Argentina and Germany are working on BNCT for the treatment of liver cancer. In addition, certain superficial tumours are routinely treated by direct irradiation with fast (high LET) neutrons, e.g., at FRM II. The treatment is mainly performed after pre-irradiation by conventional (low LET) projectiles, which needs to be looked at as a complementary method.

For successful therapy research, all scientific, clinical and logistical aspects associated with the therapy must be performed. This comprises adapting the research facility, development of pharmaceuticals, determining the boron uptake and the compounds' pharmacokinetics, developing and validating tumor models, developing enhanced dosimetry models, dose measurements and controlling the quality of procedure. **One should note separately that the full acceptance and recognition of BNCT is still needed from the end users in the medical community.**

3.7.3. Applications of the RR Pulsed Capabilities

The pulsed mode can be used for the production and analysis of isotopes with very short half-lives following activation in the reactor. The technique requires a rapid transfer system and a gamma-ray spectrometer nearby. Other applications of the pulsed RR capabilities are in the field of basic research, where time-of-flight technique is required (e.g. measurements of basic nuclear data).

4. SUMMARY OF THE DISCUSSION SESSIONS

4.1. Discussion on Newcomer Member States

- New countries request the IAEA for long term and comprehensive support for human resource development, and for that issue, ask the Agency to prepare working materials, manuals and other related documentation for introducing the 1st RR in the country and its development
- New countries consider RRs as a tool for infrastructure (both human, nuclear culture and nuclear safety) development for further expanding the peaceful application of nuclear energy
- New countries consider commercialization of the RR as the 2nd step for RR development strategy, but at the same time radioisotope production, after human resource development, is seen as the most important application of RRs with its evident social impact
- New countries request IAEA support for regional networking to promote enhanced utilization, shared user facilities and assist in development of commercial applications of RRs as part of the sustainability strategy

4.2. Discussion on Low Power RRs

A number of important and potentially commercial applications of low power RRs have been identified, namely, education and training, short-lived isotope production, NAA (e.g. INAA, DNAA, RNAA, PGNAA), neutron beam applications (e.g. digital neutron radiography), support for nuclear industry (e.g., qualification of personnel in nuclear safety and radiation protection, detector calibrations, benchmarking of simulation and modelling tools), support for national regulatory authority (e.g. qualification of personnel in nuclear safety and radiation protection), medical applications (e.g., BNCT), etc. Although among the low power RRs there is a variety of reactor types, above mentioned areas of applications can be applied at almost each of them. The following was concluded as an output from this discussion:

- Continue support of low power RR operation and enhanced utilization
- Enhance support and promote regional networks and coalition among different RR, including Member States without RRs (e.g. in the areas of education and training, NAA, etc.)
- Support with high importance the steady supply of RR fuel to assure uninterrupted operation of RRs (e.g. TRIGA fuel supply)
- Promote cooperation within the RR community in strategic planning for sustainability of nuclear engineering, science and technology with increased role of RRs
- Organize a dedicated meeting on commercial applications of NAA in order to prepare a promotional brochure and web page on commercial applications of NAA
- Promote at various occasions (e.g. topical conferences, scientific and industrial forums, etc.) dedicated RR applications
- Initiate cooperation between the different disciplines necessary for a successful application of BNCT. Key disciplines are, for example, radiotherapy and oncology, pharmacy, biology, physics, etc.
- Seek for needed accreditations (e.g. ISO 170025A) as well as develop costumer-guided infrastructure, what would potentially increase potential for commercial applications

4.3. Discussion on High Power RRs

- Any new RR project or reorganization of an existing RR needs to start with the justification of the reactor for research, technology development or industrial-commercial applications. The priorities have to be identified. This decision has to be taken under the responsibility of the individual Member State

- The Member State has to be consulted by experts and interested parties in technical and economical questions. An efficient interface with other stakeholders (and possible customers) has to be established during an early stage of the project
- For industrial (commercial) applications, the continuous observation of the market is of the highest importance. The feedback of the customers has to be involved. A common data base on the capabilities of the various RR needs to be created and updated continuously. The reactor operators should behave as competitors and colleagues at the same time
- A reliable and long term schedule of RR operation and the guaranteed on time access to the required services are expected by the customer. Industrial standards like ISO 9001:2008 have to be implemented. It helps to create confidence in the service of the RR
- Regional, international and sometimes worldwide cooperation is highly recommended and in some cases crucial. Particular questions are to be tackled by suitable/involved RRs only
- World wide cooperation is unavoidable as have already been realized in case of ^{99}Mo production (due to its short half-life and unavailability of RRs involved in the irradiation-production) and new RR fuel testing (due to its high cost for irradiations and testing)

4.4. Discussion on other items

The meeting participants have identified a number of important requirements which the commercial RR applications must fulfil in terms of

- Infrastructure and logistics such as means for loading capacities for the irradiated samples, necessary unloading equipment, availability of hot cells, laboratories for radio-chemistry, capsules for irradiation, quality control of the irradiated materials, sufficient number of well trained and experienced staff, etc.
- Client-oriented services and good practices such as well established contacts with several user groups to survey the users' requests and gauge market activity, construction of a global network for the customers as well as competitors to achieve efficient facility utilization and provide better quality – cheaper services, etc. ISO/IEC 17025:2005 accreditation may be indispensable to enter the market for providing such services.
- Coordination between the different production facilities if backup solutions are required/important (e.g. isotope production on regular basis)
- Automation of calibration and measurement procedures, including associated documentation, what boosts reliability and repeatability and thus the overall efficiency of facility use – being the base for the work along industrial quality standards and for an efficient facility pooling in order to enable fast and flexible access to the facility
- Well balanced beam time allocation for industrial clients, e.g. this time should not exceed more than, say, 50 % of the available neutron beam time – there should be enough time to perform research and methodological R&D (unless multi-user shared-beam facility is well established).
- Established a "self-stabilized and self-controlled" service system, which is based on reinvestment of the generated income as well as some guaranteed subsidies by the operating institution. Preferably permanent staff should be in charge of the service experiments due to the importance of continuous quality of the deliverables.

Other important issues were also highlighted as an output of the discussions:

- Already in the early stage of a RR project or before the reorientation of an existing reactor, the priorities between "natural competitors" like basic research and industrial applications in general and neutron scattering and irradiation services in particular need to be clarified to the extent possible
- Obvious contradictions as well as major interferences, e.g., the necessary shutdown for loading and unloading irradiation goods, have to be identified and addressed with respect to their acceptability by all end users of the facility

- It has to be seriously considered that important conditions for the industrial application of the RR are the standardization of measuring techniques and the continuity of the staff in charge
- For commercial use, a reliable medium to long term schedule of RR operation and the guarantee of timely access to the required facility is necessary
- The certification of the offered services according to industrial standards, e.g., ISO 9001:2008, helps to create the confidence of the customer in the service provided by the RR
- RR ageing related issues (e.g. staff, RR related infrastructure and auxiliary equipment) should be reflected in the utilization strategy, risk analysis and include possible remedies

5. SUMMARY OF THE MAIN RECOMMENDATIONS

The TM was highlighted as a success by all participants at the end of the week. Furthermore, the support for the meeting, in terms of number and diversity of participants as well as participating Member States, is significant indicator of the success of the broader endeavor – to provide timely practical assistance and support the sharing of experiences and good practices related to the commercial applications of RRs, establishment of enlarged collaborations, facilitated contacts and formation of networks.

It was recognized that the IAEA has undertaken a number of activities through Coordinated Research Projects, Technical Meetings and Workshops, and in some cases also through the Technical Cooperation (TC) projects to assist the Member States in the domain of both commercial and non-commercial applications of RRs. Continuation and expansion, where appropriate, of such activities was desired and encouraged.

Based on the final discussions on current status and future needs in various commercial applications using RRs, the participants formulated **the following specific recommendations:**

1. Finalization and **publication of this TM report, including individual papers, as an IAEA TECDOC, titled "Commercial Applications and Services of RRs",** was strongly recommended

2. In order to respond the increasing demand from nuclear power industries, there is great opportunity for RRs to offer commercial nuclear training services to the potential customers such as nuclear industries, governmental institutions, hospitals, etc. In this regard, **the role of RRs in nuclear education and training programmes should be urgently revisited and followed by concrete actions**, including formation of collaborations and unification of the training curricula. **The IAEA should strengthen its assistance and support in this context.**

3. **Radioisotope production and NTD of Si** remain the most important commercial applications of RRs. While some start up costs may be absorbed by the operating organization, **cost recovery for production, qualification and distribution should be the goal. The IAEA's assistance and support at different stages of related projects** in the form of expert missions, procurement of equipment, development of strategic and business plans, establishment of international networks, etc**. was highly recommended.**

4. NAA is the most simple and the most widely used application of RRs. In case of commercialization of the NAA, the following should be carefully considered: a) infrastructure improvement through implementation of automation in all phases including sample irradiation, sample measurement, data acquisition, quality control, etc., b) skills improvement of the involved personnel, c) constant interaction and established collaboration with customers. **A new CRP on the automation of NAA in the context of commercialization was strongly recommended.**

5. Non Destructive Testing (NDT) by neutrons is commonly used to improve the knowledge of materials structures and quality control of different objects. Present applications of neutron beams are corrosion studies in aluminum (aircraft industry), behavior of moisture in building materials, distribution of hydrogen, oil and or lubricants in mechanical equipment such as fuel cells and car engines. **The IAEA was requested to prepare and publish a promotional brochure on "Use of neutron beams for industrial applications"**

6. **In the field of material/fuel irradiation and testing the meeting participants identified the need for continued assistance and support from the IAEA related to the enhancement of international accessibility, harmonization of legislation of transportation of irradiated materials, utilization and share of results** in order to avoid unnecessary duplication, increase complementary studies and efficiently utilize the available resources among RRs.

7. **The newcomer countries considered the RR as a tool for nuclear infrastructure** (both human resource and equipment related) **development** for further expanding the peaceful application of nuclear energy, and therefore requested the IAEA for a long term and comprehensive support for human resource development in nuclear engineering and related areas. In this regard**, preparation of working materials, manuals, guidelines and other related documentation for introducing the 1st RR in the country was considered of the highest priority.**

8. **The newcomer countries requested IAEA's support for regional networking and coalitions to promote enhanced utilization, shared user facilities and assist in development of commercial applications of RRs as part of the sustainability strategy**

9. **The IAEA was requested to support with high importance the steady supply of RR fuel to assure uninterrupted operation of RRs** (e.g. TRIGA fuel supply). In this regard worldwide cooperation of concerned RRs was highly recommended under coordination of the IAEA.

ANNEX I. MEETING AGENDA

Monday, 28 June 2010

08:30-09:30	**Registration, Gate 1**
09:30-10:00	**Welcome & Opening Remarks** *Mr N. Ramamoorthy, Director, Division of Physical and Chemical Sciences (NAPC)* *Mr G. Mank, Section Head, Physics Section, NAPC* *Mr. P. Adelfang, Section Head, Research Reactor Section, NEFW* *Mr D. Ridikas, Scientific Secretary, Physics Section, NAPC* Self introduction of the participants, Election of Chairperson and *Rapporteur* Discussion and Approval of the Agenda, Administrative Arrangements
10:00-10:30	**Objectives of the Meeting (within the IAEA project Enhancement of Utilization and Applications of Research Reactors)** *Mr D. Ridikas, IAEA*
10:30-11:00	Coffee break
11:00-11:40	**Nuclear Education and Training Courses as a Commercial Product of Low Power Research Reactors** *Mr H. Böck, AtomInstitut, Austria*
11:40-12:20	**Present Services at the TRIGA Mark II Reactor of the JSI** *Mr B. Smodiš, JSI, Slovenia*
12:20-14:00	Lunch break
14:00-14:40	**Science and Service at a University Research Reactor** *Mr P. Bode, TU Delft, The Netherlands*
14:40-15:20	**Utilization of the Research Reactor TRIGA Mainz** *Ms. G. Hampel, JGU Mainz, Germany*
15:20-15:50	Coffee break
15:50-16:50	**Discussion on "Education and Training as a Commercial Product of RRs"** *All*
16:50-17:30	**The Role of Neutrons in the Industrial R&D Sector** *Mr R. Schneider, VDI/VDE, Germany*

Tuesday, 29 June 2010

09:00-09:40	**Industrial and Commercial Applications of FRM-II** *Mr H. Gerstenberg, TU Munich, Germany*
09:40-10:20	**Neutron Transmutation Doping of Silicon in HANARO** *Mr S.J. Park, KAERI, Republic of Korea*
10:20-10:50	Coffee break
10:50-11:30	**Radioisotopes at HANARO** *Mr U.J. Park, KAERI, Republic of Korea*
11:30-12:10	**Production of Radioisotopes in Pakistan Research Reactor: Past, Present and Future** *Mr. A. Mushtaq, PINSTECH, Pakistan*
12:10-12:50	**Irradiation of HEU Targets in MARIA Research Reactor for Mo-99 Production** *Mr G. Krzysztoszek, IEA POLATOM,Poland*
12:50-14:00	Lunch Break
14:00-14:40	**Production of Radioisotopes and NTD-Silicon in the BR-2 Reactor** *Mr. B. Ponsard, SCK*CEN, Belgium*
14:40-15:20	**INR-TRIGA Research Reactors: A Neutron Source for Radioisotopes and Materials Investigation** *Mr. D. Barbos, INR, Romania*
15:20-16:00	**Utilization of Egyptian Research Reactor and Modes of Collaboration** *Mr M.K. Shaat, EAEA, Egypt*
16:00-16:30	Coffee break
16:30-17:30	**Discussion on “Radioisotope and Silicon Production Using Research Reactors”** *All*

18:30-	**Hospitality Event** *All*

Wednesday, 30 June 2010

09:00-09:40	**Strategy for Sustainable Utilization of IRT-Sofia RR** *Mr. M. Mitev, INR, Bulgaria*
09:40-10:20	**International Cooperation as a Tool for Introducing a RR in the Republic of Azerbaijan** *Mr. I.A. Gabulov, IRP, Azerbaijan*
10:20-10:50	Coffee break
10:50-11:30	**Jordan Research & Training Reactor Utilization Facilities** *Mr. N. Xoubi, JAEA, Jordan*
11:30-12:10	**Sudan's First Research Reactor** *Mr. M.A.H. El Tayeb, SAEC, Sudan*
12:10-13:00	**Discussion on "Planning of Commercial Applications at New Research Reactors"** *All*
13:00-14:00	Lunch break
14:30-15:10	**The Utilisation of Australia's Research Reactor, OPAL** *Mr K. Mendis, ANSTO, Australia*
15:10-15:50	**An Overview of the Strategic Utilization Plan for the Moroccan Nuclear Research Reactor over the Period 2010-2015** *Mr A. Jibre, CNESTEN, Morocco*
15:50-16:20	Coffee break
16:20-17:00	**The Present Status and Future Potential Applications of Research Reactors in CIAE** *Mr F. Shen, CIAE, People's Republic of China*
17:00-17:30	**Discussion on "Commercial Applications at Newly Licensed Research Reactors"** *All*

Thursday, 1 July 2010

09:00-09:40	**Contribution of HANARO to the R&D Relevant to the SMART and VHTR Systems** *Mr. K.N. Choo, KAERI, Republic of Korea*
09:40-10:20	**Experimental irradiations of Materials and Fuels in the BR2 reactor: an overview of current programmes** *Mr S. Van Dyck, SCK*CEN, Belgium*
10:20-10:50	Coffee break
10:50-11:30	**Utilization of the Thai Research Reactor TRR-1/M1** *Mr S. Chue-inta, TINT, Thailand*
11:30-12:10	**Effective Utilization of the Dalat Research Reactor for RI Production, NAA Services, Basic Research and Training** *Mr. N. Nhi Dien, NRI, Vietnam*
12:10-12:50	**Present Status and Future Potential for Commercial Applications of JAEA Research Reactors** *Mr. M. Ishihara, JAEA, Japan*
12:50-14:00	Lunch break
14:00-14:40	**Research Reactor Utilization at the University of Utah for Nuclear Education, Training and Services** *Ms. T. Jevremovic, University of Utah, USA*
14:40-15:20	**Techniques and Nuclear Applications around Es Salam Reactor, Status and Future Potential** *Mr M. Salhi, CRNB, Algeria*
15:20-15:50	Coffee break
15:50-16:30	**Operation and Utilization of Indian Research Reactor Dhruva** *Mr S.K. Mondal, BARC, India*
16:30-17:10	**Applications and Services at PUSP ATI Reactor in Malaysia — Current Status and Outlook** *Mr M. Ashhar Hj Khalid, MNA, Malaysia*
17:10-18:00	**Discussion on "Promoting Commercial Applications at Multipurpose Research Reactors"** All

Friday, 2 July 2010

09:00-10:30	**Discussion** • **Identify opportunities for research reactor cooperation in commercial activities** • **Identify best practices in performing activities and market potential for services** All
10:30-11:00	Coffee break
11:00-12:30	**Discussion** • **Suggest collaborative commercial activities that the IAEA could promote and facilitate** • **Formulation of conclusions and recommendations** *All*
12:30-13:30	Lunch break
13:30-15:00	**Discussion** • **Finalization of conclusions and recommendations** • **Closing of the meeting** *All*
15:00	End of the meeting

ANNEX II. BOOK OF ABSTRACTS

H. Böck, AtomInstitut, Austria

Nuclear Education and Training Courses as a Commercial Product of a Low Power Research Reactor

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The Vienna University of Technology (VUT) has operated a 250 kW TRIGA Mark II research reactor at the Atominstitut (ATI) since March 1962. This reactor is uniquely devoted to nuclear education and training with the aim to offer an instrument to perform academic research and training. During the past decade, a number of requests to the Atominstitute asked for the possibility to offer this reactor for external training courses. During the past decades such courses have been developed as regular courses for students during their academic curricula at the VUT/ATI. The courses cover such subjects as "Reactor physics and kinetics", and "Reactor instrumentation and control", in total about 20 practical exercises. Textbooks have been developed in English language for both courses.

Target groups for commercial courses are other universities without an access to research reactors (e.g., Technical University of Bratislava, Slovakia or University of Manchester, UK), international organisations (e.g., IAEA Dept. of Safeguards training section), research centres (e.g., Mol, Belgium) for retraining of their reactor staff or nuclear power plants for staff retraining.

These courses have been very successful during the past five years in such a manner that the Atominstitut has now had to decline new course applications as the reactor is also used for Master's Thesis and PhD work, which requires full power operation while courses require low power operation. The paper describes typical training programs target groups and possible transfers of this courses to other reactors.

B. Smodiš, JSI, Slovenia

Present Services at the TRIGA Mark II Reactor of the JSI

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The 250 kW TRIGA Mark II reactor of the Jožef Stefan Institute (JSI) has been continuously operating since the year 1966. The reactor is extensively used for various applications, such as: irradiation of various samples, training and education, verification and validation of nuclear data and computer codes, testing and development of experimental equipment used for core physics tests at a nuclear power plant. In the paper, all of the above mentioned activities are presented and briefly described together with the references for further information.

The purpose of the contribution is to present the utilization of the TRIGA Mark II reactor of the JSI and show that even small reactors can still be used for various purposes and can significantly contribute to state of the art achievements in the field of nuclear science and technology and other related fields. In particular, the currently offered services are discussed in detail, comprising: (1) Neutron activation analysis in both instrumental and radiochemical modes; (2) Neutron irradiation of various kinds of materials intended to be used for research and applicative purposes; (3) Training and education of university students as well as on-job staff working in public and private institutions; (4) Verification of computer codes and nuclear data, comprising primarily criticality calculations and neutron flux distribution studies; and (5) Testing and development of a digital reactivity meter.

P. Bode, TU Delft, The Netherlands

Science and Service at a University Research Reactor

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University research reactors are under continuous threat of being closed down because of the costs of the facility, priority settings forthcoming from mid-term strategies (with associated reduction of budget allocation for the reactor) and inabilities to fulfill vacancies in staffing and thus loss of technical competence. Some research reactor centers try to compensate this by generating income by services. Neutron activation analysis is often the most appropriate opportunity in smaller research reactors but such a service can turn into a threat as it may affect the scientific output of the center.

The Delft University of Technology concluded in 2004 that the cost of scientific research at the Interfaculty Reactor Institute in Delft, operating the 2 MW Hoger Onderwijs Reactor, was too high compared to the cost of research at other faculties. The permanent shut down of the reactor and ending of the associated scientific research was seriously considered. However, a proposal for reorganization of the institute and scientific program was accepted, including a strategy for an organizational separation of science and service. Both aspects were given quantifiable performance indicators for the year 2008, as a basis for eventual continuation of the new organization.

These targets have been reached and by now, 2010, all sections in the scientific department are headed by new young full professors and plans have been approved for upgrading the reactor and expanding the various reactor facilities.

This strategy of combining science and service will be outlined in this presentation, with a discussion of the advantages and pitfalls.

G. Hampel, TU Mainz, Germany

Utilization of the Research Reactor TRIGA Mainz

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The TRIGA Mark II reactor of the University of Mainz has been in operation since 45 years. It can be operated in the steady state mode with thermal powers up to a maximum of 100 kW and in the pulse mode with a maximum peak power of 250 MW. So far, more than 17 000 pulses have been performed. For irradiations, the TRIGA Mainz has a central experiment tube, three pneumatic transfer systems and a rotary specimen rack which allows for the irradiation of up to 80 samples simultaneously. In addition, the TRIGA Mainz includes four horizontal beams ports and a graphite thermal column which provides a source of well-thermalized neutrons.

Due to a TRIGA reactor's inherent safety and high flexibility, a broad spectrum of scientific research and training can be executed. The TRIGA Mainz is extensively used for basic and applied research in chemistry and physics. Experiments are in preparation to determine the fundamental neutron properties with very high precision using ultra cold neutrons (UCN) which can be produced in combination with a solid deuterium converter in the neutron guide and the pulse mode of the TRIGA. Due to the successful operation of this UCN facility, a second source is under development at the piercing beam tube. Another experiment under development is the determination of ground state properties of radioactive nuclei with very high precision using a penning trap and collinear laser spectrometry. For many years, fast chemical separation procedures combining a gas jet transportation system installed in one beam tube with either continuous or discontinuous chemical separation have been carried out. In addition, the thermal column of the reactor is also used for medical and biological experiments. A project is in progress where patients with liver metastases will be treated, similar to the application at the TRIGA in Pavia, Italy. Also, cell cultures are irradiated in the thermal column at different neutron fluxes. Neutron activation analysis is applied in in-core positions to determine trace elements in different materials such as in archaeology, forensics, biological, environmental and technical materials, including semiconductors and photovoltaics. For education and training, various courses in nuclear and radiochemistry, radiation protection and reactor operation and physics are held for scientists, advanced students, teachers, engineers and technicians. Due to its experimental programme, the TRIGA Mainz will be in operation until at least 2020.

R. Schneider, VDI/VDE, Germany

The Role of Neutrons in the Industrial R&D Sector

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Most recent engineering progresses are due to the development of new materials and innovations in their processing and treatments. Materials characterization techniques for the study of metals, alloys, ceramics and composites, especially non-destructive analyses of residual stress profiles and textures and neutron imaging techniques, have gained increasing importance. But how do the neutron methods like all the other techniques provided by the large scale facilities fit to the everyday life in industry? For most applications they are used to validate and optimize materials models for FE-simulations as well as for the calibration of well-established non-destructive testing tools or to have a look much more deeply inside a sample than all the other tools can do. That way the neutrons really are unique in the materials analytics field delivering the reference in a variety of cases. But there is still something like an impedance mismatch between the facilities and the industrial companies. This contribution focuses on the optimization of the facility-industry interaction. When should the engineer in industry go to the neutron source? How to optimize the neutron experiment's impact especially considering the economical point of view? And finally: How to setup a promising marketing strategy for the research reactors?

H. Gerstenberg, TU Munich, Germany

Industrial and Commercial Applications of FRM II

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The Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II) is a 20 MW heavy water moderated research reactor which is operated since 2005 by the Technische Universität München (TUM) on its campus in Garching. Although FRM II has by design clearly been optimised for basic research using neutron beams TUM was committed already starting from the project phase of FRM II to offer the reactor also to interested parties from the industry for commercial applications. The majority of these applications is based on the use of the irradiation facilities of FRM II.

The commercially by far most important activity of FRM II is neutron transmutation doping of Si. The semi-automatic doping facility is suitable for the irradiation of Si ingots up to a maximum diameter of 200 mm and a maximum stack length of 500 mm. In 2009 a total of about 15 t of Si from various European and Asian suppliers aiming target resistivities between 20 Ω·cm and more than 1000 Ω·cm have successfully been processed at FRM II. In order to meet international industrial standards the process of Si doping at FRM II is certified according to ISO 9001:2008

In addition FRM II is supplied with a water driven rabbit system being used for the production of isotopes for industrial and medical purposes. A considerable part of the work deals with the activation of Lu-177 and other isotopes of interest for radiopharmaceutical applications and is done in collaboration with a private company being located on the reactor site of FRM II. Furthermore FRM II offers several well thermalized irradiation channels which are typically used for the preparation of samples for activation analysis or age determination of minerals by the fission track technique.

Finally TUM launched a project to equip FRM II in future with a facility for the uranium target irradiation aiming the production of Mo-99/Tc-99m in collaboration with partners from the industry. Since, however, this facility requires an extension of the operating license of FRM II, it will not start operation before 2014.

S.J. Park, KAERI, Republic of Korea

Neutron Transmutation Doping of Silicon in HANARO

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The Neutron Transmutation Doping (NTD) of silicon is a method to produce a high quality semiconductor, especially devices for the high electric power use, which is based on the nuclear transmutation of Si-30 nuclei into P-31 by neutron absorption in the high purity silicon ingot. The NTD technology makes the silicon ingot possible to be doped with an extremely uniform dopant distribution. And it became one of the rare cases in the research reactor utilization providing direct industrial applications owing to this dominant advantage comparing with other conventional chemical doping methods.

HANARO is an open-tank-in-pool type research reactor of 30 MW. It has two vertical irradiation holes in the heavy water reflector region for the NTD applications. The smaller hole of 180 mm diameter has been used for the irradiation service for 5 inch silicon ingots from the early 2003 and for 6 inch ingots from the end of 2005.

Coping with a demand of the recent NTD-Si market, an additional irradiation facility which has a potential for 8 inch silicon ingot was developed using a larger hole of 220 mm diameter in 2008. The formal irradiation services started from the end of 2009 for not only 8 inch ingots but also 6 inch ingots.

The irradiation facility in HANRO has a very unique feature that a neutron screen for the axial flatness of the neutron flux is incorporated in the irradiation can (silicon container). This assembly was fabricated very precisely and has a delicate sense for neutron screening. It can give a quite flat neutron flux with less than ±1% axial deviation over 60 cm long and a very high neutron flux of more than 3.5×10^{13} n/cm^2/s for all size of ingots.

HANARO now is getting a great favorable notice by the wafer companies in the world for the excellent quality of NTD service and high productivity. HANARO will continue a contribution to the NTD-Si market by providing a stable and reliable irradiation service.

U.J. Park, KAERI, Republic of Korea

Production and Development of Radioisotopes in HANARO

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Radioisotopes are extensively used in numerous ways for medical, scientific, agricultural and industrial purposes, and the global demand for radioisotopes is increasing rapidly. Nowadays, utilizing radioisotopes in their many applications is considered one of the key technologies in the radiation-related industry.

Radioisotope production in Korea started in 1962 when the first research reactor, TRIGA Mark II, went into operation. The second landmark in the history of Korea's radioisotope production is the operation of Korea's second research reactor, TRIGA Mark III, in 1972. With this reactor, Korea Atomic Energy Research Institute could produce several radioisotopes on a practical scale sufficient to meet domestic demands. Based on such accumulated technologies and experiences, the production of radioisotopes in Korea became flourishing right after the construction of the multi-purpose high performance reactor, HANARO (30 MW power) and a new radioisotope production facility in 1997.

More than twenty radioisotopes are currently produced at KAERI and supplied to domestic users and international markets. Radioisotopes being produced on a regular basis are ^{131}I, ^{166}Ho, ^{192}Ir, ^{60}Co, ^{32}P, ^{51}Cr, etc. The main radioisotopes, which are supplied from HANARO, are ^{192}Ir, ^{131}I, and ^{166}Ho. Currently, KAERI produces more than twenty Curies of ^{131}I capsules and solutions every week, covering more than sixty percent of domestic demand. KAERI also produces more than 200 000 Curies of ^{192}Ir non-destructive testing sources, which is equivalent to about ten percent of the international market.

Current research topics are the development of the production technologies for therapeutic beta emitters, generator systems, and industrial gauge sources. Also, research activities to expand the applications of medical sealed sources are being actively undertaken such as the use of a ^{32}P sealed sources as an ophthalmic applicator. The key technologies for ^{188}Re generator and high dose rate brachytherapy ^{192}Ir source were transferred to a private company for their commercial production.

As the commercial supplies of radioisotopes and research activities expand, international relationships have been promoted. In addition, several units of these production systems were supplied to other countries.

A. Mushtaq, PINSTECH, Pakistan

Production of Radioisotopes in Pakistan Research Reactor: past, present and future

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Production of radioisotopes started since Pakistan Research Reactor-1 went critical in December 1965. Pakistan Institute of Nuclear Science and Technology (PINSTECH) Islamabad is operating two research reactors (PARR-1 and 2) to provide services to the users for the production of radioisotopes and for neutron irradiation. Beam work usually includes using neutron beams outside of the PARR-1 for a variety of analytical purposes. Facility for neutron radiography, prompt gamma neutron activation analysis, neutron scattering for material analysis have been functioning. Improvements in the instrumentation and control system of PARR-1 are continuously being made to enhance the safety and availability of the system. Production of radioisotopes ranges from microcurie to curie level. Solid, liquid and gas targets have been irradiated for generation of alpha, beta and gamma emitting radionuclides. A large number of no-carrier-added radionuclides have been produced for applications in medicine, agriculture, hydrology and industry. Sealed radioactive sources were also manufactures to distribute in colleges and universities for basic physics experiments. The most widely used radiotherapeutic radionuclide Iodine-131 has been regularly produced for the last three decades using PARR-1. The n, gamma and fission Molybdenum-99, parent of Technetium-99m used in 80% of diagnostic nuclear medicine procedures, is also produced. Manufacturing of sealed radioactive sources of Cobalt-60, Strontium-90, Cesium-137 and Irridium-192, etc., have been planned.

G. Krzysztoszek, IAE POLATOM, Poland

Irradiations of HEU Targets in MARIA RR for Mo-99 Production

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The high flux research reactor MARIA is operated at the Institute of Atomic Energy (IAE) POLATOM. Due to the shutdown of the NRU reactor (Canada) and plans for scramming the HFR reactor (Holland) in the half of 2009 a decision was taken on cooperation between IAE and COVIDIEN which was aimed to initiate an irradiation of high-enriched uranium plates in MARIA reactor for production of molybdenum Mo-99. There was developed the Mo-99 irradiation and transport technology in MARIA reactor facility and then its expedition to the reprocessing factory in Petten (Holland). The physics calculation, safety analyses, technical projects of equipment for irradiation and transport inside the reactor facility and loading to the special transport container (MARIANNE) were made.

After receiving the positive opinion of the Nuclear Safety Committee of IAE and approvals released by the National Atomic Energy Agency there were made:

- Channel for uranium plates' irradiation
- Equipment to be used for plates' transport from the reactor core to the hot cell
- Reloading stand for the transport container – MARIANNE
- Rail trolley for transport and lifting of shielding container MARIANNE

It was accomplished the program for checking and testing full installation which included:

- Loading unloading and transport of plates within the boundary of reactor pools
- Reloading of the plate dummies to the shielding container
- Monitoring of container leak-tightness
- Irradiation of the plates' dummies (Al) in the reactor

In the meantime a number of licenses needed for the transport of irradiated uranium plates from MARIA reactor in Poland through Germany to Holland were received.

The final stage of examination was the test irradiation of uranium plates in the period 8-14 February, 2010 under nominal conditions. These plates successively were delivered to Petten. The very good results of production achieved were confirmed by calculations and physical analyses and at the beginning of March we started regular irradiations at first in singular and later in two channels.

B. Ponsard, SCK*CEN, Belgium

Production of Radioisotopes and NTD-Silicon in the BR2 Reactor

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The BR2 reactor is a multipurpose 100 MW high flux Materials Testing Reactor operated by the Belgian Nuclear Research Centre (SCK•CEN) in which various research and commercial programmes are performed. The commercial activities such as radioisotopes production and silicon doping have been actively developed since the 1990's to generate additional revenues. Currently, they represent a significant contribution to the reactor operating costs and are carried out in accordance with a 'Quality System' that has been certified to the requirements of the "EN ISO 9001 : 2000" in December 2006. Due to its operating flexibility, its reliability and its production capacity, the BR2 reactor is considered as a major facility for these commercial activities worldwide. The availability of thermal neutron fluxes up to 10^{15} n/cm².s allows the production of a wide range of radioisotopes for various applications in nuclear medicine, industry and research such as ^{99}Mo (^{99m}Tc), ^{131}I, ^{133}Xe, ^{192}Ir, ^{186}Re, ^{153}Sm, ^{169}Er, ^{90}Y, ^{32}P, ^{188}W (^{188}Re), ^{203}Hg, ^{82}Br, ^{79}Kr, ^{41}Ar, ^{125}I, ^{177}Lu, ^{117m}Sn, ^{89}Sr, ^{169}Yb, ^{147}Nd, ... Some irradiations devices allow the loading and unloading of irradiated targets during the operation of the reactor. Hot-cells and storage facilities are available to prepare and organize the shipment of the irradiated targets to dedicated processing facilities. In the frame of the current ^{99}Mo/^{99m}Tc global shortage, new dedicated irradiation devices have been installed in April 2010 to increase the ^{99}Mo production capacity by 50%. Special efforts have also been made to develop the production of therapeutic radioisotopes as ^{177}Lu which is supplied by both direct and indirect routes. Neutron Transmutation Doping (NTD) Silicon activities for the semiconductor industry started at SCK•CEN in 1992 with the commissioning of SIDONIE, a single channel light water device that is located in a 200-mm diameter beryllium channel within the reactor pressure vessel. Its design allows the irradiation of 5-inch diameter silicon batches which are continuously rotating and traversing the core at computer controlled speeds. To meet increasing demand for 6 and 8-inch diameter silicon ingots, SCK•CEN designed a new facility which became operational in 2008. POSEIDON is a multichannel graphite moderated device located in the BR2 reactor pool on the outside of the reactor pressure vessel. Its large irradiation capacity allows for the simultaneous exposure of six silicon batches of 6-8 inch diameter.

D. Barbos, INR, Romania

INR TRIGA Research Reactors a Neutron Source for Radioisotopes and Materials Investigation

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At the INR there are two high-intensity neutron sources. These sources are in fact the two nuclear TRIGA reactors: TRIGA SSR 14MW and TRIGA ACPR. TRIGA stationary reactor is provided with several in-core irradiation channels. Other several out-of-core irradiation channels are located in the vertical channels in the beryllium reflector blocks. The maximum value of the thermal neutron flux (E<0.55 eV) in the central core channel XC-1 (water-filled) is 2.46×10^{14} $n/cm^2\cdot s$ and of fast neutron flux (E>1 MeV) is $6.89\times10^{14} n/cm^2\cdot s$.

For neutron activation analysis both reactors are used and k_0-NAA method has been implemented. At INR Pitesti a prompt gamma ray neutron activation analysis devices has been designed, manufactured ant put into operation.

For nuclear materials properties investigation neutron radiography methods was developed in INR. For these purposes two neutron radiography were manufactured, one of them underwater and other one dry.

The neutron beams are used for investigation of materials properties and components produced or under development for applications in the energy sector (fission and fusion). At TRIGA 14 MW reactor a neutron diffractometer and a SANS devices are available for material residual stress and texture measurements.

TRIGA 14 MW reactor is used for medical and industrial radioisotopes production (^{131}I, ^{125}I, ^{192}Ir, etc.) and a method for ^{99}Mo-^{99}Tc production from fission is under development.

At INR Pitesti, several special programmes for a new type of nuclear fuel behavior characterization are developed.

Key words: neutron activation analysis; k_0 standardization; neutron diffraction; neutron radiography; radioisotopes.

M.K. Shaat, EAEA, Egypt

Utilization of Egyptian Research Reactor and Modes of Collaborations

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The Egyptian Atomic Energy Authority (EAEA) owns a new material testing research reactor (MTR) called ETRR-2. This reactor was commissioned in 1997 and is a swimming pool type using plate type fuel elements with 20% enrichment. It is cooled and moderated by light water and uses beryllium as a reflector. Its maximum thermal power is 22 MW, with maximum thermal neutron flux of 2.7×10^{14} $n/cm^2/s$ and can be operated up to one cycle, around 18 days, for the high fluence necessary for applying long irradiations for peaceful utilization and a wide range of applications. The reactor is a multipurpose utilization, containing different facilities for applying neutron activation analysis (NAA), radioisotope production (e.g., Ir-131, Co-60, P-32, Mo-99, etc.), neutron transmutation doping (NTD) of silicon ingots of 12.5 cm diameter and 30 cm in length, neutron radiography education for university students, research for scientists, and training for new operators.

Also, the reactor is equipped with 26 positions for in-core irradiation with high fluence positions, two radial beam ports, two tangential beam ports and a thermal column. The reactor has special hot cells for material testing under irradiation conditions. We can apply the impact tests, tensile strength tests, and other material characterization for irradiated samples which can be used in different industrial applications, nuclear power plants and fusion reactors.

The strategic and business plan for reactor utilization and collaborations with national and regional partners was updated. Also, several design modifications for the NTD facility to irradiate larger silicon ingots was implemented. In this paper we will present the different current and future activities for peaceful utilization of the ETRR-2 reactor, stressing on the benefits of material irradiation testing and characterization at high neutron fluxes and high fluence.

M. Mitev, INR, Bulgaria

Strategy for Sustainable Utilization of IRT-Sofia Research Reactor

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The Research Reactor IRT-2000 in Sofia is in process of reconstruction into a low-power reactor of 200 kW under the decision of the Council of Ministers of Republic of Bulgaria from 2001.

The pillars of IRT-Sofia utilization are:

- Development and preservation of nuclear science, skills, and knowledge
- Implementation of applied methods and research
- Education of students and training of graduated physicists and engineers in the field of nuclear science and nuclear energy
- Development of radiation therapy facility

Nuclear energy has a strategic place within the structure of the country's energy system. In that aspect, the research reactor as a material base, and its scientific and technical personnel, represent a solid basis for the development of nuclear energy in our country. The acquired scientific experience and qualification in reactor operation are a precondition for the equal in rights participation of the country in the international cooperation and the approaching to the European structures, and assurance of the national interests. Therefore, the operation and use of the research reactor brings significant economic benefits for the country. For education of students in nuclear energy, reactor-physics experiments for measurements of static and kinetic reactor parameters will be carried out on the research reactor. The research reactor as a national base will support training and applied research, keep up the good practice and the preparation of specialists who are able to monitor radioactivity sources, to develop new methods for detection of low quantities of radioactive isotopes which are hard to find, for deactivation and personal protection. The reactor will be used for production of isotopes needed for medical therapy and diagnostics; it will be the neutron source in element activation analysis having a number of applications in industrial production, medicine, chemistry, criminology, etc.

The reactor operation will increase the public understanding, confidence, and support for nuclear energy through common medical applications, and lectures and demonstrations to high school and university students as well as to the general public.

I.A. Gabulov, IRP, Azerbaijan

International Cooperation as the Tool for Introducing a Research Reactor in the Republic of Azerbaijan

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Azerbaijan has sufficient hydrocarbon resources. However, oil and gas resources are estimated to be sufficient in Azerbaijan only for 25-30 years, therefore within a country's energy policy Government has decided to consider nuclear power as one of possible alternative energy sources. On the near-term, the multi-year programme will begin with a feasibility study of a research reactor, regulatory and technical infrastructure establishment and training of specialists required for the task. New national project AZB/4/002 "Conducting a feasibility study for planning and establishing a research reactor" has been started in 2009 within the framework of technical cooperation with IAEA. Research reactor, its size, possible use for neutron activation analysis, radioisotope production, neutron beam research, material reactor tests and training of nuclear engineers and all technical, safety and security aspects will be included in the study.

The Institute of Radiation Problems of the Azerbaijan National Academy of Sciences is the only institution in Azerbaijan doing some research on nuclear energy and therefore the only one capable to take the responsibility for the research reactor project. To deal with the different challenges, transfer of knowledge and training of specialists in reactor engineering is crucial. The results of the feasibility study shall provide answers on the following:

- Assessment and evaluation of the needs for the research reactor and the existing technical and safety infrastructure in the country
- Characterization and suitability of available site, identification of the national capabilities and their possible contribution to the implementation of the research reactor
- Implementation of regulatory infrastructure including organizational, staffing and regulatory functions, and the training needs to have qualified human resources for regulatory body and operating organization for the research reactor
- Identification of safety and physical security aspects

N. Xoubi, JAEA, Jordan

Jordan Research and Training Reactor (JRTR) Utilization Facilities

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Jordan Research and Training Reactor (JRTR) is a 5 MW light water open pool multipurpose reactor that serves as the focal point for Jordan national nuclear centre, and is designed to be utilized in three main areas; education and training, nuclear research, and commercial & industrial services.

The reactor core is composed of 18 fuel assemblies, MTR plate type 19.75% enriched uranium silicide (U_3Si_2) in aluminium matrix, and is reflected on all sides by beryllium and graphite, the reactor power is upgradable to 10 MW with a maximum thermal flux of 1.45×10^{14} n/cm^{2}s, and is controlled by Hafnium control absorber rod and B_4C shutdown rod.

The reactor is designed to include laboratories and classrooms that will support the establishment of a Nuclear Reactor School for educating and training students in disciplines like nuclear engineering, reactor physics, radiochemistry, nuclear technology, radiation protection, and other related scientific fields where classroom instruction and laboratory experiments will be related in a very practical and realistic manner to the actual operation of the reactor. Nuclear Engineering problems of shielding, criticality, control rod aspects, temperature feedback, and reactivity will be demonstrated using the reactor, providing students with an enormously valuable experience.

JRTR is designed to support advanced nuclear research as well as commercial and industrial services, which can be preformed utilizing any of its 35 experimental facilities; three incore facilities for radioisotope production and potentially material test, 10 facilities in the inner region (IR) with a flux greater than 6×10^{13}, 10 outer region (OR) facilities for irradiation experiment and radioisotope production, 1 large facility (LH) for irradiation of bulky objects, 3 facilities are dedicated for neutron activation analysis, 3 facilities for neutron transmutation doping of up to 8”. One horizontal facility (ST4) is dedicated for cold neutron source (CNS), 2 horizontal facilities (ST1 & ST2) can be used for neutron sciences elastic scattering instruments, inelastic scattering instruments, prompt gamma NAA, one facility (ST3) is for Neutron Radiography. The thermal column will be used for irradiation of bulky objects and potentially boron neutron capture therapy (BNCT)

M.A.H. Eltayeb, SAEC, Sudan

Preparation of a Strategy Plan in Light of IAEA Guidance for Introducing Sudan's First Nuclear Research Reactor with Optimum Utilization

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The Sudan Atomic Energy Commission (SAEC) is receiving assistant from the International Atomic Energy Agency (IAEA) to carry out a feasibility study for introducing Sudan's first nuclear research reactor. The ultimate aim of establishing the reactor facility is to strengthen the national infrastructure for nuclear science and technology, support higher education and professional training programmes for nuclear applications and services and explore the possibility for the production of short lived radioisotopes for various applications in the fields of medicine, geology, agriculture, industry, environmental studies and non-destructive testing. The IAEA has provided Sudan with a draft questionnaire for technology and safety infrastructure evaluation in addition to IAEA publications in this regard. A survey team has been established at SAEC and has studied the relevant IAEA documents and questionnaires. A further questionnaires dossier was developed after identifying the potential users of the proposed RR. This dossier was designed for each individual organization and contains questionnaires related to available and potential utilizations, identified groups and persons, human resource (HR) for acquisition, HR for operation and construction, infrastructure support for construction and operation and legal, nuclear regulatory and physical security framework. Each subgroup of the survey team was assigned to a couple of organizations. An action plan with a detailed timeline was developed for the first three months, and currently we are in the data acquisition process. It is expected that by analysing and interpreting the collected information together with a survey of the available RRs, a detailed strategy plan with a clear optimum utilization of the proposed RR will be prepared. This plan will be the road map, and together with the feasibility study to be prepared within 18 months where the 20 issues of the IAEA milestones approach will be addressed, constitutes the full document to be submitted to the decision makers so as to make an informed decision for building a nuclear research reactor facility.

K. Mendis, ANSTO, Australia

The Utilisation of Australia's Research Reactor, OPAL

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OPAL is a 20 MW pool type research reactor with a peak thermal neutron flux of 2.9×10^{14} n/cm^2/s. The core is surrounded by a heavy water reflecting vessel where all the irradiation facilities are located. OPAL reached criticality in October 2006 and is currently being effectively utilized for neutron beam research, production of radioisotopes for medical and research purposes and for commercial applications.

The neutron beam facilities of OPAL consist of neutron beam tubes that penetrate the reflector vessel, a cold neutron source, beam shutters and neutron guides. A suite of neutron beam instruments utilize both the thermal and cold neutron beams for both atomic and molecular structure determination and dynamic measurements, residual stress measurement and neutron imaging. A total of seven neutron beam instruments are currently operational, with a further seven under construction.

The irradiation facilities consist of general purpose irradiation facilities comprising 55 tubes that run from two pneumatic hot cells to positions located within the reflector vessel, 17 irradiation facilities running parallel vertically through the reflector vessel for the bulk production of radioisotopes, 6 large volume facilities for the production of NTD silicon, and 2 irradiation facilities for short NAA and DNAA irradiations.

All irradiation facilities have been successfully commissioned and are presently being utilized for the production of radioisotopes and NTD silicon. The k_0-method of standardisation for NAA has been implemented successfully, taking advantage of highly thermalised and stable fluxes available in OPAL.

ANSTO's experience during construction, commissioning and operation of the reactor and irradiation facilities will be presented. Experiences in working with internal and external customers and strategies aimed at increasing utilization of OPAL will also be discussed.

A. Jibre, CNESTEN, Morocco

An Overview of Strategic Utilization Plan for the Moroccan Nuclear Research Reactor over the Period of 2010-2015

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The National Centre for Nuclear Energy, Science and Technology (CNESTEN), a Moroccan state-owned company, is setting up a strategic utilization plan for its recently commissioned and licensed nuclear research reactor, TRIGA Mark II, 2 MW, over the period of 2010-2015. This strategic plan is aiming to efficiently and effectively meet existing and potential needs: research and development, education and training, and generally all related products and services, both at national and regional level, within a sustainable framework.

For that purpose, CNESTEN's vision is to develop and strengthen its position in the market place by fully integrating both operational and logistical issues in being strategically led, market oriented, competitively focused, operationally efficient, revenue generating applications emphasized, and human resources driven.

All internal stakeholders are involved in elaborating this strategic plan to fully ensure their adhesion for better implementation. They include managers, engineers, scientists, administrative staff from reactor utilisation and operation, safety and security, marketing and commercial staff, maintenance, and human resource development. Of course, along with this process, external stakeholders are also involved for better understanding of national needs as well as for their valuable and sustainable contribution. They include mainly end users, national agencies and universities. Furthermore, regional and international cooperation with IAEA, AFRA and bilateral partners is an asset in elaborating and implementing this strategic plan through exchange of good practices, lessons learned, transfer of knowledge, etc.

In term of existing and potential services and products to be delivered from the research reactor, CNESTEN is more focusing on education and training for which an international training centre is under development, radioisotopes production for both medical and industrial uses for which CNESTEN has a leading national position, analytical techniques such as NAA, PGNAA, neutron beam techniques as neutron imaging and neutron diffraction, irradiation services for NTD.

F. Shen, CIAE, People's Republic of China

The Present Status and Future Potential Applications of RRs in CIAE

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The general information of RRs in CIAE is introduced briefly. The application history of these RRs is reviewed. The current applications such as Nuclear education and training, capsule irradiations of medical and industrial many kinds of radioisotopes, the irradiation of silicon NTD, the applications of NAA and Neutron Scattering Experiment, the advanced nuclear system experiments and so on, is introduced.

Along the criticality of China Advanced Research Reactor (CARR) is approached in CIAE, the best multi-purpose RR in China, the much more applications is proposed except for the planed applications. This paper will introduce the planed applications such as neutron scattering experiments and its instruments installed on CARR, especially with the high cold neutron flux by installation of CNS. The RI production capability is improved since of the high thermal neutron flux and large irradiation space for typical radioisotope, such as I-125, Mo-99, etc., and new radioisotopes in China. Three vertical channels are installed for the irradiation of NTD of silicon, the estimated production quantity is present. The irradiation damage for material is also considered on CARR and fuel irradiation, especially the burn-up and transient ramp, could be test on CARR. In addition to aforementioned applications, the estimated applications of the education and training, as well as the thermal spectrum measurement is planed.

Keywords: Present Status, Research Reactor, CARR, Nuclear Technology Utilization.

K.N. Choo, KAERI, Republic of Korea

Contribution of HANARO to the R&D Relevant to the SMART and VHTR Systems

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The High-flux Advanced Neutron Application Reactor (HANARO) is an open-pool type multi-purposed research reactor located at KAERI, in Korea. Since the commencement of HANARO operation in1995, various neutron irradiation facilities such as the rabbit (small non-instrumented capsule) irradiation facilities, the FTL (Fuel Test Loop) facilities, and the capsule irradiation facilities for irradiation tests of nuclear materials and fuels have been developed at HANARO. The irradiation facilities have been actively utilized for the various nuclear fuel and material irradiation tests requested by users from research institutes, universities, and the industries. Most irradiation tests have been related to the R&D relevant to the present nuclear power reactor such as ageing management and safety evaluation of the components. HANARO has also applied on several commercial-based irradiation tests relevant to the extension of the life time of the current nuclear power reactor (Kori-1), new alloy and fuel developments (Doosan Heavy Industry Co. and Korea Nuclear Fuel Co.), and control rod material evaluation (Westinghouse Electric Company, U.S.A.). Based on the accumulated experience and the user's sophisticated requirements, HANARO has recently started new support of R&D relevant to the future nuclear systems of the SMART (System-integrated Modular Advanced ReacTor) and VHTR (Very-High-Temperature Reactor System). The SMART is one of the most advanced SMRs (Small and Medium sized Reactors) in the world. The Korean government decided recently to develop the system as one of its new growth engines. An irradiation plan of the SMART steam generator material to obtain the neutron irradiation characteristics of the alloy using HANARO irradiation capsules was planned and undertaken. The VHTR is one of the leading reactor designs for next-generation nuclear energy systems to meet the world's future energy needs. A Generation IV R&D plan for the structural materials in VHTR's was initiated as an International Nuclear Energy Research Initiative (I-NERI) Project, which is a bilateral research agreement between the Ministry of Science and Technology (MOST) of Korea and the Department of Energy of the U.S. In this paper, not only the status of HANARO irradiation facilities but also the support of R&D relevant to the future nuclear systems of HANARO will be described.

S. Van Dyck, SCK*CEN, Belgium

Experimental irradiations of Materials and Fuels in the BR2 reactor: an overview of current programmes

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The BR2 material test reactor offers a variety of experimental irradiation possibilities for testing of materials, fuels and instruments. The current paper gives an overview of the recent and ongoing programmes in order to illustrate the experimental potential of the reactor. Four domains of applications are reviewed:

- Irradiation of materials and fuels for pressurised water reactors (PWR).
- Irradiation of materials for accellerator driven systems (ADS), cooled by liquid lead alloys.
- Irradiation of fuel for material test reactors (MTR).
- In-core mechanical testing of materials

For PWR relevant tests, a dedicated loop is available, providing a full simulation of the thermohydraulic conditions of a PWR. This loop is used for the irradiation of structure materials to low and moderate fast neutron dose and for the base irradiation of fuel rods. Both "classical" PWR fuels as well as advanced fuels are studied, the former for high burn-up accumulation, the latter for general screening and qualification purposes at low to medium burn-up. The modelling of the irradiation conditions allows to make a precise analysis of the irradiation and on-line monitoring of the experiment. In this way, the interaction of modelling and experiment leads to a continuous quality improvement and validation of the irradiation services provided.

ADS related tests require particular control of the irradiation environment and the necessary safety precautions in order to avoid ^{210}Po contamination. Additionally, the irradiation temperature control in devices filled with liquid lead alloys poses additional challenges due to important nuclear heating of the high density environment.

Irradiation of fuel for MTR applications at BR2 is aiming at qualifying new fuels or new fuel element designs for existing or new material test reactors. These irradiations are aiming at qualifying fuels in representative conditions, so adaptations to the primary cooling circuit of the reactor may be required in order to meet the experimental needs. For the irradiation testing of single fuel plates, re-usable baskets are available, cooled by the primary flow. For the qualification of full size fuel elements, a semi-open loop is used in order to simulate the expected thermal – hydraulic conditions in the client reactor. This loop is installed in the central 200mm channel in order to accommodate the largesize fuel element and to provide a maximum uniformity in flux to the experiment.

In-core mechanical testing of materials is done in comparison and complementarity to post-irradiation examinations in order to assess flux related effects on the deformation behaviour of materials. Creep, tensile and fatigue loading are applied by passive (static gas pressure, swelling ceramic inserts) or active (bellow loading) techniques. The results are then compared to post irradiation testing in order to assess the interaction between the dynamics of irradiation induced defects and plasticity induced defects.

S. Chue-inta, TINT, Thailand

Utilization of the Thai Research Reactor (TRR-1/M1)

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The Thai TRIGA Mark III research reactor TRR-1 has reached eighteenth core configuration in 2010 after more than thirty years of service since 1977. The recent hexagonal core comprises 107 fuel elements of 8.5-20% mixed enrichment and five control rods, with a maximum neutron flux of 3×10^{13} n/cm^2/s at 1.2 MW. Core calculations were carried out by neutronics computer codes (3D deterministic method SRAC and Monte Carlo 3D method MVP) and thermal hydraulics codes (steady state calculation COOLODN and reactivity insertion analysis EUREKA2/RR). There are ten in-core tubes (CT, C8, C12, F3, F12, F22, F29, G5, G22, G23) and nine out-core tubes and facilities (A1, A4, CA2, CA3, TC, wet tube rack, rotary specimen rack, void tank, beam ports). The reactor serves research and development on neutron activation analysis, neutron radiography and plant mutation, as well as services on medical radioisotope production (I-131, P-32, and Sm-153), gem quality enhancement and elemental analysis with a total income around $75 million in 2009. The reactor serves education, training and technology transfer including university reactor experiments and technical tours for the public.

N. Nhi Dien, NRI, Vietnam

Effective Utilization of the Dalat Research Reactor for RI Production, NAA Services, Basic Research and Training

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The 500-kW Dalat Research Reactor (DRR) was upgraded and restarted operation on March 20, 1984. So far, the DRR has been operating mainly for radioisotope production, neutron activation analysis, basic research and nuclear training.

Radioisotopes and radiopharmaceuticals have been produced serving nuclear medicine centers and other users such as in industry, agriculture, hydrology, scientific research, etc. The main products are ^{131}I solution and capsules, ^{32}P applicators and solution, ^{99m}Tc generator and its labels, and others by requirement. It is giving a yearly average of about 250 Ci for 23 nuclear medicine centers in the country.

Different methods of neutron activation analysis are used for element analysis, including Instrumental NAA, Radiochemical NAA and Prompt gamma NAA. The K-zero method for INAA has been developed to analyse airborne particulate samples for investigation of air pollution; crude oil samples and base rock samples for oil field study.

In case of analytical services, requests of many branches of the national economy for various types of samples have been answered to serve for geology exploration, oil prospecting, agriculture, biology, and environmental monitoring. About 4000 samples have been irradiated and analysed every year.

The reactor has four horizontal beam tubes and a large thermal column, which provide beams of neutron and gamma radiation for a variety of experiments. At these experimental facilities, the PGNAA system has been set-up for analytical services and the two-detector HPGe gamma spectrometry system for studying of (n, 2γ) reactions has been installed to generate nuclear data.

As the only research reactor in the country, the DRR has also been used effectively for education on reactor engineering and for training of reactor operation and management staffs.

M. Ishihara, JAEA, Japan

Present Status and Future Potential for Commercial Application of JAEA Research Reactors

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Utilization of research reactors can be categorized as four major application targets:

- Lifetime extension of LWRs, e.g., aging management of LWRs, development of next generation LWRs
- Progress of science and technologies, e.g., next generation reactors such as HTGR, fusion reactor, basic research on nuclear energy, neutron beam utilization
- Industrial use, e.g., production of silicon semiconductor, radioisotope (RI) production
- Education and training of nuclear scientists and engineers.

Japan Atomic Energy Agency (JAEA) has developed a fleet of four different types of research reactors, Japan Research Reactor 3 (JRR-3), JRR-4, Nuclear Safety Research Reactor (NSRR) and Japan Materials Testing Reactor (JMTR) designed specifically for intended purpose. JRR-3, a light water moderated and cooled pool type reactor with 20MW thermal power, is applied to beam experiments, irradiation tests, RI production, activation analysis and silicon semiconductor production. JRR-4, a light water moderated and cooled swimming pool type reactor with 3.5 MW thermal power, is designed for medical irradiation (Boron Neutron Capture Therapy), RI production and education & training. A pulse reactor with the maximum power of 23GW at pulse operation, NSRR, is utilized for nuclear fuel safety researches. JMTR, a light water cooling tank typed reactor with 50 MW thermal power, is devoted to irradiation tests for nuclear fuels and materials, and RI production.

JMTR is now under refurbishment of reactor facilities. The refurbished JMTR is expected an appreciable income from commercial users. A few successful examples on JMTR will be shown in this presentation from a viewpoint of commercial applications. Since the strengthened regional and/or international cooperation is a key issue to enhance the steady commercial applications such as RI production, the importance of regional and international framework is also mentioned.

T. Jevremovic, University of Utah, USA

Research Reactor Utilization at the University of Utah for Nuclear Education, Training and Services

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Nuclear Education: In the years of nuclear renaissance we all recognize a need for modernizing the approaches in fostering nuclear engineering and science knowledge, in strengthening disciplinary depth in students' education for their preparation for workforce, and in helping them learn how to extend range of skills, develop habits of mind and subject matter knowledge. The education infrastructure at the University of Utah has been recently revised to incorporate the experiential learning using our reserach reactor as integral part of curriculum, helping therefore that all of our students build sufficient level of nuclear engineering literacy in order to be able to contribute productively to nuclear engineering work force or continue their education toward doctoral degrees.

Nuclear Training: The University of Utah TRIGA Reactor is established 35 years ago as university-wide facility to promote research, education and training, as well as various applications of nuclear engineering, radiation science and health physics aspects. Our curriculum includes two consecutive classes for preparation of our students for research reactor operating license. Classes include review of research reactors physics, TH, control &instrumentation, heat transfer, accident analysis, radiation & radiation doses, fuel management & fuel burnup, experiments that could be performed at the facility, nuclear policy & regulation, as well as weekly training to operate our research reactor. Every year the US Nuclear Regulatory Commission's representatives hold the final exam for our students.

Enhancing Services: Our activities serving the academic community of the University of Utah, commercial and government entities, other Universities and National Laboratories, include but are not limitted to : benchmark experiments for validation and uncertainty quantifications of computation modeling tools, radiation hardening of the electronic components tested for their durability and strength, dose reconstruction for internal & external dose evaluation for epidemiological uses, fission track analysis, neutron activation analysis of various samples from daily products to various environmental samples (e.g., Great Salt Lake samples, wooden chopsticks, tobacco, etc.).

M. Salhi, CRNB, Algeria

Techniques and Nuclear Applications around Es Salam Reactor, Status and Future Potential.

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Es Salam is a 15 MW heavy water tank reactor equipped with more than fifty experimental channels situated vertically and horizontally around the core. The smart physical properties of those channels and the availability of the auxiliary facilities enhance the implementation of many applications on nuclear training, analytical techniques, neutron scattering, production of radioisotopes, neutron transmutation doping of silicon, etc. Since the period of commissioning and the master of reactor operation, a training plan and R&D projects is carried out. In this paper we present the progress in the implementation of the techniques and the applications around the reactor. A near future vision is also done.

Key words: Es Salam, Research Reactor, neutron scattering, NAA, nuclear applications

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Operation and Utilization of Indian Research Reactor Dhruva

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Dhruva, a tank type, high flux research reactor is operating since 1985 at Mumbai, India. It employs natural metallic uranium as fuel and heavy water as coolant, moderator and reflector. This reactor, with a rated power of 100 MW(t), offers a maximum neutron flux level of 1.8×10^{14} n/cm^2·s. The reactor is well utilized for two and half decades on 24x7 basis with high availability and excellent safety record.

This paper describes initial utilization and subsequent development on various irradiation programmes at Dhruva. Adequate excess reactivity is available for regular isotopes production and various irradiation experiments. Since all the in-core irradiation assemblies are cooled by the primary coolant, it is possible to engineer an irradiation or experimental assembly in any of the fuel positions. Hence, by providing additional isotope tray rods in fuel positions, it is possible to augment production of various radioisotopes. In addition to conventional beam hole facilities (tangential and radial) for neutron beam experiments, a neutron beam guide facility was commissioned to transport neutrons to an adjacent Guide Tube laboratory for carrying out experiments in low radiation background. The Pneumatic Carrier Facility caters to irradiation of short-lived samples for neutron activation analysis, which requires minimum transit time between the completion of irradiation and counting. A pressurized water loop of 2 MW(t) heat capacity for irradiation & testing of experimental fuel bundles for Indian power reactor is under installation. A beam tube is being designed for carrying out Prompt Gamma Neutron Activation Analysis (PGNAA). Irradiation of thorium rods in one of the fuel positions for generating data on irradiation behaviour of the fuel is planned. This paper also describes other future projects like production of NTD silicon and development of a special irradiation rig for production of fission Molybdenum-99.

M. Ashhar Hj Khalid, MNA, Malaysia

Applications and Services at PUSP ATI TRIGA Reactor in Malaysia - Current Status and Outlook

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The Malaysian Nuclear Agency (Nuclear Malaysia) has been operating PUSPATI TRIGA MkII research reactor since it was commissioned in 1982. The reactor has a maximum thermal power of one MW with maximum neutron flux of around 1×10^{13} n/cm^2/s in the central thimble at the centre of the reactor core top grid plate. A pile-up position reduces the neutron flux slightly.

Other irradiation facilities is Lazy Susan, which has lower neutron flux at 1×10^{12} n/cm^2/s and auxiliary facilities at beam ports, i.e., the small angle neutron scattering (SANS) and neutron radiography (NR). Since the magnitude of the neutron flux and flux distribution had posed some limitations to the enhancement of the reactor utilization, the expansion of neutron application for advance research is limited. However, effort has been made to enhance the usage by increasing the number of neutron application facility as well as to improve the existing setup. Generally, the reactor is used mainly for training in reactor operation, production of radioisotopes for medical and industrial use, as well as research and development (R&D) in neutron beam application at SANS and NR. Malaysia has also been involved in the development of plasma focus system as a basic tool in understanding of fusion sciences.

This paper presents the current applications and services rendered by existing research reactor as well as activities related to plasma focus in Nuclear Malaysia, the future plan and outlook as well as efforts undertaken to enhance them. Also included are suggestions of areas for cooperation and networking among member states and reactor owners and operators.

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Photo of Meeting Participants