IAEA TECDOC 1715

IAEA TECDOC SERIES

TECDOC No. 1715

Commercial Products and Services of Research Reactors

IAEA

International Atomic Energy Agency

COMMERCIAL PRODUCTS AND SERVICES OF RESEARCH REACTORS

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIETNAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA-TECDOC-1715

COMMERCIAL PRODUCTS AND SERVICES OF RESEARCH REACTORS

PROCEEDINGS OF A TECHNICAL MEETING HELD IN VIENNA 28 JUNE–2 JULY 2010

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2013

For further information on this publication, please contact:

Physics Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

Printed by the IAEA in Austria
July 2013

IAEA Library Cataloguing in Publication Data

Commercial products and services of research reactors : proceedings
of a technical meeting held in Vienna, June 28-July 2, 2010.
– Vienna : International Atomic Energy Agency, 2013.
p. ; 30 cm. – (IAEA-TECDOC series, ISSN 1011-4289
; no. 1715)
ISBN 978-92-0-143610-8
Includes bibliographical references.

1. Nuclear engineering – Congresses. 2. Nuclear reactors – Economic aspects. 3. Nuclear reactors – Research. I. International Atomic Energy Agency. II. Series.

IAEAL 13-00826

FOREWORD

Although the number of operational research reactors is steadily decreasing, more than half of those that remain are greatly underutilized and, in most cases, underfunded. To continue to play a key role in the development of peaceful uses of nuclear technology, the remaining research reactors will need to provide useful products and services to private, national and regional customers, in some cases with adequate revenue generation for reliable, safe and secure facility management and operation. In the light of declining governmental financial support and the need for improved physical security and conversion to low enriched uranium (LEU) fuel, many research reactors have been challenged to generate income to offset increasing operational and maintenance costs. The renewed interest in nuclear power (and therefore in nuclear education and training), the global expansion of diagnostic and therapeutic nuclear medicine, and the extensive use of semiconductors in electronics and in other areas have created new opportunities for research reactors, prominent among them, markets for products and services in regions and countries without such facilities. It is clear that such initiatives towards greater self-reliance will need to address such aspects as market surveys, marketing and business plans, and cost of delivery services. It will also be important to better inform present and future potential end users of research reactor services of the capabilities and products that can be provided.

This publication is a compilation of material from an IAEA technical meeting on “Commercial Products and Services of Research Reactors”, held in Vienna, Austria, from 28 June to 2 July 2010. The overall objective of the meeting was to exchange information on good practices and to provide concrete examples, in technical presentations and brainstorming discussions, to promote and facilitate the development of commercial applications of research reactors. The meeting also aimed to enhance the utilization of research reactors and their sustainability through financially viable services and international cooperation. In this report, reference is also made to a similar IAEA technical meeting on “Commercial Applications of Nuclear Analytical Techniques”, held in Vienna, Austria, from 23 to 26 November 2004, and a few recently updated papers from that meeting have been included here. This publication summarizes the individual reports presented during the above meetings, and details the overall findings and conclusions jointly identified and agreed upon by the meeting participants.

The individual papers are available on the CD-ROM attached to this publication. The IAEA acknowledges the valuable contributions of the individual participants and of the experts who reviewed this report, particularly P. Bode (Netherlands). The IAEA officers responsible for this publication were D. Ridikas of the Division of Physical and Chemical Sciences and N.D. Peld of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. Background

In July 2012 according to the IAEA Research Reactor Database (RRDB), of more than 700 research reactors (RRs), including critical facilities, constructed around the world, 229 were still operating and 8 were under construction or planned, while 15 more were under the status of temporary shutdown [1]. Of the RRs no longer operating, most are undergoing decommissioning or waiting to be decommissioned, but some in an extended shutdown state have no clear plans for their future following the resumption of operation. The majority of operational RRs despite a decreasing total of reactors are still heavily underutilized and, in most cases, underfunded, which presents a demand for profitable products and services to balance increasing operational, security, fuel and maintenance 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 programme funding. This not only results in reduced income for the facilities involved, but sometimes also in RR 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 the World Association of Nuclear Operators (WANO) in the nuclear power generation sector shows 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 RRs can provide, some of which are presented below in Table 1. This data has been compiled from facility data providers to the IAEA RRDB and demonstrates the wealth of services provided by sizable numbers of RRs.

TABLE 1. THE COMMON APPLICATIONS OF RESEARCH REACTORS AROUND THE WORLD [1]

Type of Application	Number of RRs involved[a]
Isotope production	92
Neutron scattering	50
Neutron radiography	71
Material irradiation	153
Transmutation (gemstones)	27
Transmutation (doping of Si)	35
Teaching/training	165
Neutron activation analysis (NAA)	124
Geochronology	25
Boron neutron capture therapy (BNCT), including R&D	22
Other[b]	103

[a] Out of 252 RRs considered (229 operational, 15 temporary shutdown, 4 under construction and 4 planned; December 2012).

[b] Other applications include calibration and testing of instrumentation and dosimetry, shielding experiments, reactor physics experiments, nuclear data measurements, and public relations tours and seminars.

1.2. Purpose and scope

The Technical Meeting's primary function was to provide a forum for the exchange of good practices and collection of concrete examples through technical presentations and brainstorming discussions in order to achieve the following overall objectives:

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

The meeting focused on the present status and future potential for commercial applications of RRs. The following areas were 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) and fission track dating, with emphasis on complementary services when compared to non RR based methods;
— Neutron beam techniques such as neutron imaging, small angle neutron scattering (SANS) and neutron diffraction;
— Support of R&D relevant to present nuclear power reactors, e.g., ageing management and the development and qualification of new fuels;

— 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 and nuclear data provision; and
— Other potentially revenue generating applications.

The purpose of this TECDOC is to provide guidance related to the potential of nuclear RRs for supplying products and services such as radioisotope production, education and training or application targeted measurements with reactor based nuclear techniques. Technical and organizational aspects for such services are discussed in some detail, as well as the relevant reactor size or characteristics, including identification of some major requirements and constraints. Through a number of individual technical papers, concrete examples are given of opportunities and strategies for organizing commercial services using RRs of different types and various power ratings.

1.3. Structure

The present report consists of seven chapters including references. The publication briefly recalls the role of RRs (chapter 2) and resumes with the main considerations for providing services by these facilities (chapter 3). The largest, chapter 4, details types of products and services RRs can provide. For each type, some discussion on requirements, specifications and market potential is included. Chapter 5 describes major constrains and obstacles one must address in order to make the application commercial, while general conclusions are presented in chapter 6. Finally, the publication includes a CD-ROM, in which through a number of individual technical papers, concrete examples are given of opportunities and strategies for organizing various commercial services using RRs of different type or power.

2. ROLE OF RESEARCH REACTORS

Nuclear research reactors serve three main purposes:

— A tool for education and training in reactor physics, reactor operations, nuclear safety, neutron physics, and radio- and nuclear chemistry;
— A source of neutrons of different energies. Neutrons are categorized as thermal, epithermal and fast based on their energy distribution; mixtures of these categories often occur; and
— As prototype facilities to demonstrate the maturity of nuclear technology and training before full scale power reactors can be built.

Neutrons produced in a RR can be used for various types of research and development that allow for numerous types of activities:

— Neutron capture and fission for:
  - Radioisotope production,
  - Neutron activation analysis,
  - Neutron depth profiling,
  - Fission track dating,
  - Transmutation doping,
  - Gemstone colour enhancement,
  - Material testing,
  - Realization of positron beams, and
  - Neutron therapy;

— Neutron transmission and scattering for:
  - Radiography and tomography,
  - Small angle neutron scattering,
  - Neutron diffraction,
  - Neutron depolarization, and
  - Neutron reflectometry.

Using one or more of these opportunities, the reactor can be exploited for the following activities.

(i) Scientific activities by the operating institution

Most research reactors are located in national research institutes or in university institutes, and the users are therefore mainly found inside these centres or institutes. This scenario indicates their envisioned importance for education and training of scientists and engineers in reactor physics, and in use of neutrons for neutron beam physics, nuclear physics and radiochemistry. Reactor utilization is strongly guided by the types of experimental facilities. RRs are designed for a specific use, having designed experimental facilities with consequently limited or no opportunities to change or expand once the reactor has been brought into operation. The applications stretch from material science to archaeology, biology, medicine and many more areas. The reactor sometimes serves in research as a stepping stone for scientists to design and test instruments for eventual use at spallation sources, currently the most powerful pulsed sources of neutrons.

Research reactors are also used in training programmes for operators of nuclear power plants (NPPs), though simulators have increasingly entered the market for this type of training. Still, RRs have an indispensable role in operator training since they offer a relatively safe opportunity for training in the control of a reactor by hands on practical exercises.

(ii) Scientific activities of the governing institution in collaboration with other organizations

The use of RRs in one or more of the aforementioned applications is not per se a privilege of researchers at the operating institute. Collaboration with specialists in applied fields often based at other organizations may be indispensable in defining and testing a hypothesis. In other cases, scientists from other organizations may wish to use the RR facilities on their own, or even develop and test their own instruments with the reactor. Collaboration is also frequently of an international character, as visiting scientists from other countries may seek to take advantage of unique, complementary or more powerful facilities than the ones normally used.

(iii) Services to scientists from other organizations with limited collaborative capacity

Reactor institutes may also decide to provide services to scientists from other organizations. Such services are characterized by limited or no joint scientific interest. Examples include but are not limited to:

— The production of radioisotopes for use in laboratories or medical and industrial applications;
— Measurements and analysis with neutron based techniques such as neutron activation analysis, neutron diffraction, neutron radiography and delayed neutron counting;
— Irradiation and return of materials for study and use in transmutation doping of Si and gemstone colour enhancement or irradiation and testing of nuclear fuel and structure materials; and
— Education and training of staff from other organizations in reactor physics, reactor operations, radiation shielding and protection.

(iv) Services to third party organizations

Finally, research reactors may provide above mentioned services on a full commercial basis in which no joint interest in the intended purpose exists.

3. CONSIDERATIONS FOR PROVIDING SERVICES

There are two main driving forces for providing services, both to external scientists and to third parties:

(i) Services increase the number of stakeholders of the facility, as one indication of its relevance that contributes to the justification of its existence. One should not underestimate the importance of having a large, and possibly broad, stakeholder community. Demonstrating relevance to a broad scientific community, as well as socially relevant research and applications, can be the decisive factor in continuing support for the facility. Examples exist of reactor institutes that received governmental support for upgrading their facilities because of their broad stakeholder community.

(ii) Services generate extra-budgetary income. Radioisotope production, nuclear analytical measurements and technical irradiations such as transmutation doping indeed may be attractive for third parties willing to pay for such services. There are several success stories of RRs in which a substantial fraction of the running costs are covered by such services. However, at least a partial return of revenue to cover the running costs of the service is an indispensable precondition which is not always met in the practice.

At large, providing services may contribute to a higher degree of reactor utilization. Figures 1, 2 and 3 demonstrate that in the previous decade, of the 57 IAEA Member States operating research reactors, a majority were able to provide services in neutron activation analysis, isotope production, and teaching and training. Additionally, a high proportion has been featuring these services since the 1980s [1].

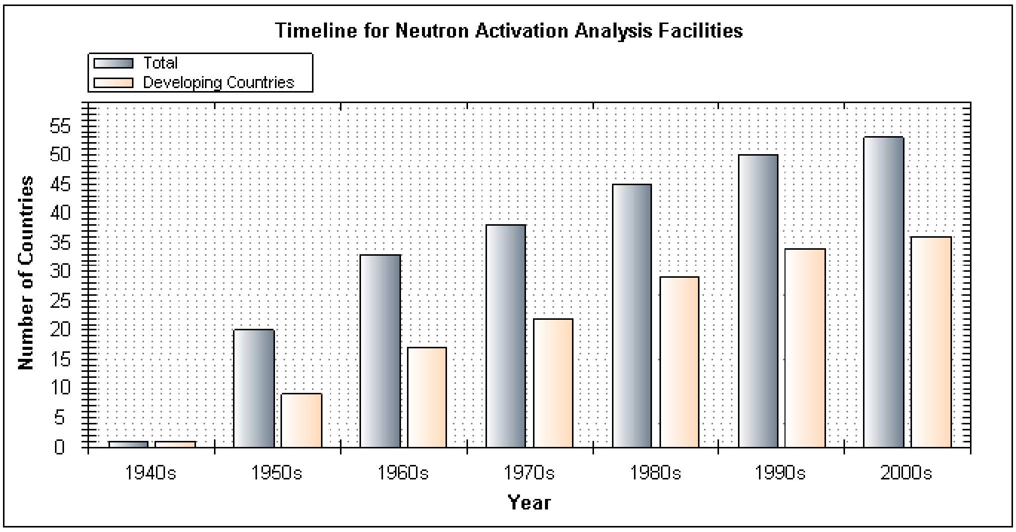

Fig. 1. Timeline of states with facilities providing neutron activation analysis.

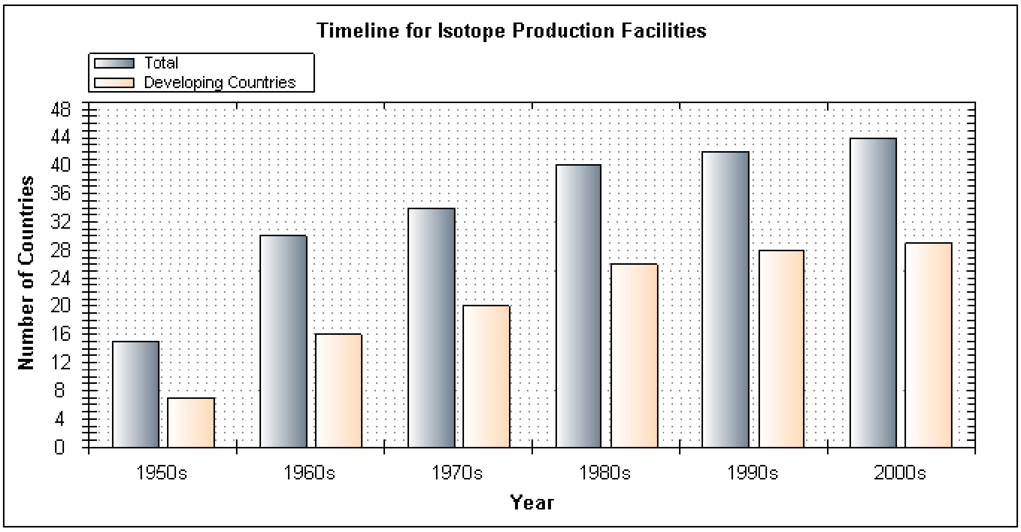

Fig. 2. Timeline of states with facilities providing radioisotope production.

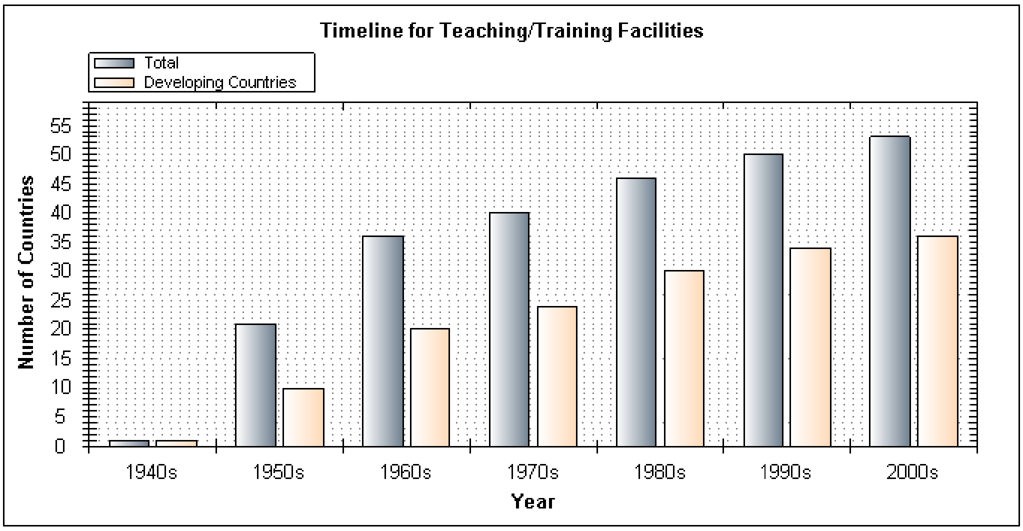

Fig. 3. Timeline of states with facilities providing teaching and training.

4. TYPES OF SERVICES

4.1. Education and training

Nuclear education and training is one of the most important tasks of low power RRs. Highly skilled workers for a number of different jobs are required to have a basic understanding of the nuclear engineering field, nuclear science principles, nuclear policy and regulations, and nuclear security and forensics. Nuclear science and engineering applications can be found not only in the power and health industries, but also in military, industrial, environmental, and commercial programmes around the world. Developing the insight and awareness of the basic science and engineering principles behind nuclear technologies will not only provide enhanced marketability for students graduating from nuclear engineering programmes, but also better prepare them for careers that incorporate an increased understanding of nuclear science and engineering. The nuclear industry, national laboratories, government agencies, and NPPs and associated facilities in many countries, as well as universities, are all facing a huge wave of retirees in addition to the renaissance of nuclear engineering and science that is bringing a new demand for long term profitable nuclear engineering careers both as workers and as entrepreneurs. Although standard nuclear engineers are expected to have a college degree in nuclear engineering, the 21st century, as we see it, projects a demand for different career profiles: more diversified and broad knowledge gained through dual degrees, such as a combination of a major in any relevant discipline and a minor in nuclear engineering, and also encouragement for such students to complete at least a master’s degree in nuclear engineering or where possible complete reactor operation training. Having hands on experience and capabilities to apply classroom knowledge into practical meanings is becoming a crucial component of modern nuclear engineering curricula [2].

Research reactors offer a large variety of possible experiments both in academic and practical areas, simple access requirements and low operational costs. In particular, countries managing nuclear power programmes have largely demonstrated a special need to use low power RRs for training their future staff on various technical levels, both from operational and regulatory organizations[1]. Small and medium RRs therefore have a role as a stepping stone for scientists to prepare themselves before doing their research at new leading edge multipurpose reactors such as the Jules Horowitz Reactor in France, the China Advanced Research Reactor (CARR), the Open Pool Australian Lightwater reactor (OPAL) of the Australian Nuclear Science and Technology Organisation (ANSTO) and the Russian Federation’s PIK.

Furthermore, an emphasis on training nuclear scientists and specialists is applicable not only for emerging nuclear countries but also for countries with long term nuclear programmes, as senior staff retires without an ample new generation having been trained over the past decades as replacements 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. There exists 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 and hospitals. Both national and regional markets should be explored in this regard. Nuclear simulators available at most modern NPPs cannot fully replace hands on training at RRs. As a result, a number of small RRs must extend the existing training courses, both in scope and capacity of trainees to be trained, in order to

[1] The approximate number of professional staff to be trained at different level or areas of competence per new NPP to be built and operated is 1000 [3].

respond the increasing demand from the nuclear power industry and prevalent requests for the development of course curricula related to nuclear safety and nuclear security aspects.

RRs involved in design and organization of such courses should seek closer collaboration and formation of networks in order to unify the curricula, share knowledge and experience, and optimize facilities regarding various capabilities. Examples of such collaborations already exist, such as the Baltic Research Reactor Network, the Caribbean Research Reactor Coalition, the Central African Research Reactor Network, the Eastern European Research Reactor Initiative, the Eurasia Research Reactor Coalition and the Mediterranean Research Reactor Network [4]. IAEA stimulated these networks to facilitate the provision of education and hands on training courses in different and complementary experimental facilities and nuclear sciences.

Web based interactive course modules integrated with extensive experimental practices are a modern approach in student education. Within these modules, enhanced learning and interest in reactor physics and radiation transport classes ably reflect in full the recently emphasized multidisciplinary dimension of these important nuclear engineering topics. In addition, visualization of reactor physics and radiation transport phenomena has been found to be interesting and inspirational ways ensuring students' broader understanding. Core courses may take the following practices:

(i) Theory is presented in class;

(ii) Students then practice the exhibited concepts using web based interactive tools;

(iii) Following this introduction, they may advance to a successive stage using more complex approaches such as running nuclear engineering codes;

(iv) Analyze the data; and

(v) Finally participants perform well designed and planned experiments at the reactor to benchmark some or all of the simulations and modelling results.

The IAEA's Remote Research Reactor programme [5] is a cost effective way to train groups of students in research reactor operations that can help states train and evaluate their human capital needs for ensuing reactor projects. It gives virtual RR access to countries that otherwise have no installed facilities, but have groups of students ready to be trained in RR operations. The programme works by creating a virtual reactor in a remote location via an internet link. Using hardware and software installed in a RR in the host state, signals are sent over the internet to the remote location, where a real time display of the reactor's control room is visible to students. Using video conference equipment, students in the remote location then can interact with operators in the reactor control room to learn about operations and conduct experiments by proxy by asking the reactor operators to change reactor settings and seeing the real time displays change accordingly. A proof of the principles for the Remote Research Reactor project was completed in September 2010, when North Carolina State University, USA, and the Jordan University of Science and Technology commenced and tested successfully their remote reactor project [4].

In some reactors students also receive courses that yield an operator licence. Classes include a general review of reactor physics, specifics of RRs and the training reactor's physics, thermal-hydraulics, control, instrumentation, accident analysis, radiation and radiation doses, fuel management and burn up, a review of experiments that can and cannot be performed at the facility, a review of nuclear policy and regulation, and hands on training in operating the reactor. A regulatory official subsequently holds the final exam for a reactor operating license.

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. For example, 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; and
— **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.

4.2. Radioisotope production

4.2.1. General

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. An isotope production programme involves several interrelated activities such as target fabrication, irradiation in a RR or accelerator, transportation of irradiated target to a 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 [6]. In low flux reactors ($<10^{13}$ cm^{-2}s^{-1}) the resultant neutron fluence available is also often low because of limitations on the reactor's operational periods, e.g., only for one shift or, even irregularly, one or a few days per week. Such an operation schedule dictates the production of short half-life radioisotopes if the saturation activity is desired. Radioisotopes that can readily be produced, e.g., on request from local users, for uses in scientific research or non-destructive leak testing in industry, include: ^{24}Na, ^{32}P, ^{38}Cl, ^{56}Mn, ^{41}Ar, ^{64}Cu and ^{198}Au.

A low power reactor facility with a neutron flux below 10^{12} cm^{-2}s^{-1} is usually only capable of irradiating materials to produce certain useful radioisotopes in limited quantities for special research or training applications

Reactors with medium flux (10^{13}–10^{14} cm^{-2}s^{-1}) generally operate for longer cycles up to 100 h/week cycles. Such operational schedules could allow for the production of more marketable radioisotopes. In addition to those low flux reactor produced isotopes listed above, it should be possible to produce the following as well: ^{90}Y, ^{99}Mo, ^{125}I, ^{131}I and ^{133}Xe.

In the case of those reactors with high fluxes ($>10^{14}$ cm^{-2}s^{-1}), which usually operate for more continuous periods, e.g., cycles of weeks or hundreds of hours or longer, the requirements of its experimental users and radioisotope production are complimentary. In addition to the above, production of the following isotopes should be possible: ^{35}S, ^{51}Cr, ^{60}Co, ^{89}Sr, ^{153}Sm, ^{169}Yb, ^{170}Tm and ^{192}Ir.

Low enriched and highly enriched uranium (HEU) targets are also irradiated in some high flux reactors so as to produce medical radioisotopes.

For the production of commercial quantities of medical and industrial radioisotopes, however, the flux should be at least equivalent to or greater than those indicated for medium sized reactors, i.e., $>10^{13}$ $cm^{-2}s^{-1}$.

There is certainly a dedicated niche for low power RRs to produce short lived radionuclides such as ^{56}Mn, ^{20}F, ^{24}Na, ^{42}K, ^{82}Br, ^{116m}In, or ^{128}I that are not generally available by shipment from abroad but of considerable use in demonstration, teaching and research. The use of short lived nuclides produced by a reactor on the spot is particularly suitable for teaching purposes because of the inherent safety related to their fast decay. The preparation of radioisotope calibration sources for a variety of applications in radiation analysis, instrumentation development and calibration, is only possible when produced locally.

Most reactor produced radioisotopes are products of the (n,γ) reaction, for example, ^{60}Co, ^{192}Ir, ^{89}Sr, ^{153}Sm, and ^{186}Re. This reaction is also referred to as radiative capture and is primarily a thermal neutron reaction. In some cases the absorption of a neutron leads to emission of a charged particle. Such a reaction caused by fast neutrons having more energy than a particular value known as threshold energy is termed an (n,p) or (n,α) reaction. Finally, thermal neutron induced fission of ^{235}U provides a host of useful radioisotopes, such as ^{131}I, ^{133}Xe and ^{99}Mo. ^{99m}Tc as a decay product of ^{99}Mo, which is packaged as a $^{99}Mo/^{99m}Tc$ generator, is a crucial radioisotope that is used in about 80% of the diagnostic nuclear imaging procedures in nuclear medicine.

4.2.2. Medical radioisotopes

The international supply of ^{99}Mo relies on a limited number of RRs and processing facilities[2]. ^{99}Mo ($T_{1/2}$=66 h) is obtained by the irradiation of HEU targets (93% ^{235}U) of 4–5 g ^{235}U. However, there is a worldwide tendency to convert this production process towards the use of LEU targets containing <20% ^{235}U in view of proliferation aspects to the use of HEU. Its production is essential for nuclear medicine, as ^{99m}Tc, obtained from $^{99}Mo/^{99m}Tc$ generators, is used in about 80% of diagnostic nuclear imaging procedures. These applications represent yearly approximately 30 million examinations globally [7].

The irradiation devices for ^{99}Mo production are designed to be cooled by primary reactor water and to be loaded and unloaded during reactor operation using an ingenious water lock. A typical irradiation of 150 hours in a thermal neutron flux of 2.5×10^{14} $cm^{-2}s^{-1}$ yields up to 1000 Ci per target at the end of the irradiation (EOI), i.e., 120 Ci '6-day' calibrated per target. After irradiation, the targets are moved from the irradiation position to the cooling position where they are cooled by the primary reactor water for 6 hours. They are then brought to the unloading position for loading into containers at EOI+12 hours, which are shipped to the processing facilities where ^{99}Mo and other fission isotopes such as ^{131}I ($T_{1/2}$=8.02 d) and ^{133}Xe ($T_{1/2}$=5.24 d) are recovered. ^{133}Xe is used for diagnostic imaging of lung functioning. Eventually, the ^{99}Mo is loaded on the absorber of a chromatographic column and eluted with a solvent that specifically removes the decay daughter product ^{99m}Tc only for final use in radiodiagnostics and therapy. This comprises the operation of a $^{99}Mo/^{99m}Tc$ radioisotope generator.

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

The installation of uranium targets for molybdenum production in a reactor core may involve replacement of fuel channels with the targets, which causes a decrease in excess reactivity of the core. Such a reduction may be compensated for either by the partial exchange of fuel for less burn up or increasing the number of fuel elements. This has been the case in, e.g., the Maria reactor in Poland during their production in 2010 [8]. In the two initial irradiation cycles, 2010/V and 2010/VI, the partial exchange of fuel for less burn up was made. Installation of two molybdenum channels in cycles 2010/VII and 2010/VIII required loading into the core two additional fuel channels. All these changes involve increasing the mass of ^{235}U in such a way to provide the appropriate excess reactivity of the core.

The short half-life of ^{99}Mo ($T_{1/2}$=66 h) as well as its daughter ^{99m}Tc ($T_{1/2}$=6 h) requires a regular supply of ^{99}Mo/^{99m}Tc generators to hospitals or central radiopharmacies. In the year 2012, there are primarily only five nuclear reactors involved in the production of ^{99}Mo on an industrial scale worldwide: NRU (Canada), HFR (Netherlands), BR2 (Belgium), OSIRIS (France) and SAFARI-1 (South Africa). Except for SAFARI-1, which recently began utilizing LEU targets, they irradiate HEU targets for the production of about 95% of the available ^{99}Mo issued by four processing institutions: Atomic Energy of Canada Limited (AECL)/Nordion, Inc. of Canada, Covidien in Netherlands, the National Institute for Radioelements (IRE) in Belgium and Nuclear Technology Products (Pty), Ltd. (NTP) in South Africa. However, these ageing reactors are subject to unscheduled shutdowns and longer maintenance periods, making the ^{99}Mo supply chain vulnerable and unreliable.

Access to the reactors and processing facilities for the ^{99}Mo supply has been a matter of concern for the nuclear medicine community for more than ten years.

Production of ^{99}Mo by neutron activation of a suitable Mo compound such as MoO_3 is an alternative opportunity for reactors with no licence for processing HEU or LEU targets. Activation ^{99}Mo has, of course, a much lower specific activity than fission ^{99}Mo due to the smaller cross-section of the parent nuclide. This implies also the need for a larger chromatographic column, and consequently, large elution volumes of a saline solution and a low concentration of ^{99m}Tc. This has been overcome by gel technology. After activation, an insoluble zirconium–^{99}Mo–molybdate gel is prepared by mixing $^{99}MoO_3$ with a zirconyl solution which forms the basis for the generator; thus the column can still be kept compact. Subsequent to production is loading onto an alumina containing chromatographic column.

4.2.3. Other medical radioisotopes

^{131}I is typically produced by a dry distillation process using TeO_2 targets [9]. In addition to the existing use of ^{131}I in the treatment of hyperthyroidism and metastatic thyroid cancer, ^{125}I, which has a much better gamma merit ratio as compared to ^{131}I, is the most recent addition to the variety of radioisotopes for medical uses. ^{125}I is used worldwide for radioimmunoassay and as a brachytherapy source for treatment of eye and prostate cancer.

Beta emitters are also used in the treatment of primary cancer by localized irradiation (^{192}Ir) or by the selective administration of radiopharmaceuticals (^{177}Lu, ^{188}Re, ^{90}Y, ^{32}P, ^{166}Ho, etc.). Chromatographic absorbers similar to those of ^{99}Mo/^{99m}Tc generators are used for ^{188}W/^{188}Re generators and ^{90}Sr/^{90}Y generators. There are still new generators based on other parent–daughter decays being developed.

Another application for these beta emitters, ^{186}Re, ^{188}Re, ^{153}Sm, ^{89}Sr, ^{90}Y, ^{177}Lu, ^{169}Er, etc., is for pain palliation to provide significant improvement in the quality of life of cancer patients suffering from pain associated with bone metastases as well as for the treatment of joint pain from rheumatoid arthritis. Some radionuclides such as ^{125}I and ^{103}Pd, encapsulated in a titanium welded capsule and decaying by electron capture with the emission of characteristic X rays, have applications in brachytherapy for the treatment of prostate cancer by local implantation of the activated seeds.

4.2.4. Industrial applications

Radioisotopes are used in industries in echo benign technologies such as radiation vulcanization of rubber latex, radiation sterilization of medical products and radiation cross linking, but also in the treatment of domestic and industrial waste like flue gases and in the radiation hygienisation of sewage sludge. Radionuclides like ^{82}Br, ^{203}Hg, ^{198}Au, ^{47}Sc, ^{140}La and ^{24}Na used for leakage and blockage detection in buried pipe lines, residence time distribution studies in chemical reactors, sediment transport, effluent dispersion and seepage studies in canals and dams are produced according to specific requirements of the users. Beta ray sealed sources have been used widely in the industries of paper, pulp, plastics, steel, environment, etc. The window of a source is a micro-thin stainless steel sheet through which β rays are emitted. The radiation core is made of a ceramic plate that is fabricated by the formation of zirconia. The radioactive source is produced by absorption of ^{90}Sr or ^{32}P solutions to the core plate.

The major radioisotope reactor for industrial applications is ^{192}Ir ($T_{1/2}$=74 d), mainly for radiography of welds to detect the occurrence of cohesion and cracks, but also for brachytherapy. The successful use of radiography depends on the ability of the radiation source, be it X ray or gamma, to provide sufficient radiation to penetrate the material and produce an image of acceptable contrast and definition on the processed radiographic film within an acceptable and economic timescale. Welds and thick wall inspections of pipelines are typical applications for the use of gamma radiography.

The size of the radiation source, low cost and weight of the equipment in comparison to X ray tubes of comparable power are advantages of gamma radiation equipment. Gamma equipment does not need a power supply, and it is therefore very useful for mobile inspection and access in space restricted areas. Iridium target material, natural and enriched (80% ^{191}Ir), is irradiated in various sizes, dimensions and geometries depending on the application, but typically in the order of a few mm. The target material is irradiated in standardized cold welded aluminium capsules, as in Figure 4, that contain an inner aluminium cylinder and helium gas. The capsules are typically irradiated for a long period and at a high thermal neutron flux, e.g., in the BR2 reactor for 3 or 4 weeks at 10^{15} $cm^{-2}s^{-1}$ [10]. The specific activities achieved at EOI range from 500 Ci/g up to 750 Ci/g for natural iridium and up to 1500 Ci/g for enriched iridium, depending on the size of the discs, the loading of the capsules and the irradiation position. The large anti-reactivity effect associated with the production of this particular radioisotope has a direct impact on operational parameters such as cycle length and safety margins of the reactor and its fuel cycle. Other radioisotopes such as ^{203}Hg, ^{24}Na, ^{82}Br and ^{41}Ar are also regularly requested for specific applications such as leak detection in industrial products.

Fig. 4. Equipment for ^{192}Ir irradiation.

Finally, RRs have a role for regular production of ^{60}Co radioisotopes. ^{60}Co is used for radiation sterilization of medical products. The worldwide demand of ^{60}Co has gradually grown by 5–10% every year. Studies are underway to realize mass production of ^{60}Co by irradiation in reactors at NPPs.

4.2.5. Radioisotopes for scientific research

The unique features of using radiotracers are not always fully explored at nuclear research reactor centers [11]. The radiotracer method is a versatile and powerful tool in the study of a wide variety of applications in, e.g., chemistry, biology, agriculture, medicine and industrial technology. The greatest advantage of these radiotracers, particularly, stable isotope tracers, commonly applied in nutrition studies, is their enabling of non-invasive studies of both steady state and dynamic systems in equilibrium situations and for transport and exchange phenomena to provide information on the chemical and physical status of elements. The radiotracer method does not imply huge equipment investments but rather requires that the three interrelated aspects, experimental design, data treatment including tracer kinetic analysis and data interpretation, are careful considered.

Radiotracer production with reactors often implies additional fundamental research to use smart nuclear reactions and chemical separations to obtain an almost no-carrier added tracer. Nuclear analytical groups already equipped with gamma ray spectrometers can thus extend their research programme. Using Ge spectrometers, multi-labeling experiments are possible that allow for unique applications if different radionuclides exist for the same element, such as ^{65}Zn and ^{69m}Zn or ^{64}Cu and ^{67}Cu. For example, ^{67}Cu ($T_{1/2}$=2.58 d), has been produced via the ^{67}Zn(n,p)^{67}Cu reaction to evaluate its properties as a candidate radiotracer for copper related pharmacokinetic and toxicokinetic research [11]. The developments in novel scintillation detectors, room temperature semiconductor detectors like CdZnTe and position sensitive detectors open the door for an entire new scope of radiotracer applications such as single photon emission computed tomography (SPECT). Once applied to in-vitro studies with cell cultures, the nuclear analytical group may position itself in the worlds of medical research, biochemistry and biotechnology. Radiotracers can be used to study the properties of drug delivering compounds as used in cancer therapy.

Radiotracers can be added as a label to solid particles and to liquids but may also be applied in the gaseous form, e.g., using ^{41}Ar or ^{81m}Kr. Gaseous radionuclides open the door for interesting applications in technology processes to study gas–liquid contacts or gas flow kinetics in which hardly any other technique can compete.

An example of the broad variety of radioisotopes produced in a single RR for radiotracer applications or other typical activities is given in Table 2.

TABLE 2. RADIOISOTOPES PRODUCED IN PARR-1, PAKISTAN [12]

No	Radio-nuclide	Chemical form	Maximum activity/batch	Year	Application
1	^{24}Na	Sodium carbonate	50 mCi	1966	R&D
2	^{32}P	Sodium phosphate	50 mCi, >1Ci	1978, 1986	Therapy, agriculture
3	^{35}S	Sodium sulphate	10 mCi	1995	β^- source R&D
4	^{46}Sc	Scandium glass	50 Ci	1967	Hydrology
5	^{47}Sc	Scandium chloride	mCi	2005	R&D
6	^{51}Cr	Sodium chromate EDTA Complex	100 mCi 100 mCi	1972	Diagnosis, hydrology Diagnosis
7	^{59}Fe	Ferric chloride	5 mCi	1994	R & D
8	^{60}Co	Metal	10 mCi	1980	γ source, educational
9	^{64}Cu	Copper chloride	50 mCi	1988	R&D
10	^{65}Zn	Zinc chloride	mCi	1989	R&D
11	^{75}Se	L-Selenomethionine	10 mCi	1982	Diagnosis
12	^{77}As	Arsenic chloride	mCi	2007	R&D
13	^{82}Br	Potassium bromide Ammonium bromide Dibromobenzene	~1Ci ~1Ci ~1Ci	1972	Industry, hydrology Industry, hydrology Industry, hydrology
14	^{99}Mo	^{99m}Tc generator (n,γ)	150 mCi	1973	Diagnosis
15	^{99}Mo	^{99m}Tc generator (PAKGEN) local	~1Ci 500 mCi	2002 (2010)	Diagnosis
16	^{111}Ag	Silver chloride	5 mCi	1995	R&D
17	^{113}Sn	Tin chloride	mCi	1996	R&D
18	^{115}Cd	Cadmium chloride	mCi	1996	R&D
19	^{125}Sb	Antimony chloride	1 mCi	1994	Sealed source
20.	^{131}I	Sodium Iodide, oral solution Sodium ortho-idohippurate MIBG	~7Ci 20 mCi 30 mCi	1979 1980 2000	Diagnosis/therapy Diagnosis Diagnosis
21	^{133}Ba	Barium chloride	μCi	1996	Sealed source
22	^{134}Cs	Cesium chloride	100 mCi	1993	R&D
23	^{140}La	Lanthanum chloride	~ 1Ci	2003	Hydrology
24	^{153}Sm	^{153}Sm-EDTMP	~ 1Ci	1999	Therapy
25	^{152,154}Eu	Metal	~10 mCi	1995	Calibration source
26	^{166m}Ho	Holmium oxide	μCi	1995	Calibration source
27	^{166}Ho	Particles	>100 mCi	1995	Therapy
28	^{177}Lu	^{177}Lu-EDTMP	500 mCi	2008	Therapy
29	^{186,188}Re	^{186,188}Re-EHDP	>100 mCi	1995	Therapy

No	Radio-nuclide	Chemical form	Maximum activity/batch	Year	Application
30	^{188}W	Generator of ^{188}Re, (^{188}W–^{188}Re)	5 mCi	1988	R&D
31	^{198}Au	Colloidal, gold chloride, potassium auro cyanide	~ 1 Ci	1974	Therapy, tracer
32	^{199}Au	Gold chloride	~ 10mCi	1994	R&D
33	^{197}Hg	Neohydrin	100 mCi	1977	Diagnosis
34	^{203}Hg	Neohydrin	10 mCi	1977	Diagnosis
35	^{210}Po	Metal	Ci	1982	R&D

4.2.6. Quality control

A gamma spectroscopy system is needed for quality assurance (QA) purposes to provide reliable measurements of radioactivity levels and purity. Indeed, a complete 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. Possible abnormal occurrences during the production process should be verified as 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 startup costs may be absorbed by the operating organization, cost recovery for production and distribution should be the goal.

4.3. Neutron transmutation doping

4.3.1. General

Nuclear transmutation means the change of a nucleus to another or multiple other nuclides through a nuclear reaction. The transmutation is usually instigated by interaction with neutrons, photons or high energy charged particles. If a nucleus absorbs a neutron, the resulting compound nucleus may be in an unstable state and undergo some processes to become stable. If its atomic number is changed in this process, the original atom is changed into a new element and therefore will have different properties.

Doping is a process of intentionally adding a small amount of an impurity into a material to improve its properties for dedicated purposes. Particularly, doping in semiconductor technology is the insertion or creation of impurities in an intrinsic or extrinsic semiconductor material to improve its electrical properties. An intrinsic semiconductor is a pure semiconductor without any significant intentionally introduced dopant species present. Thus, its electrical properties are determined by the properties of the material itself. An extrinsic semiconductor, on the other hand, is a doped semiconductor.

Therefore, NTD is defined as the process by which neutron irradiation creates impurities in an intrinsic or extrinsic semiconductor to increase its value for various uses.

The most prominent target or candidate materials for NTD are Si, Ge, GaAs, GaN, GaP, InP, InSe and HgCdTe. While many significant commodities are produced from germanium, the main target of NTD is yet silicon. 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.

A large commercial amount of NTD is applicable only for silicon because of the following reasons:

- 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 demand for an extremely high quality silicon semiconductor useful for power devices and sensors has been significant and is still increasing;
- Si ingots are available in the form of extremely pure perfect single crystals;
- In comparison with compound semiconductors, Si has the advantage that the introduction of the dopant in the correct sub-lattice is less problematic in certain cases; and
- NTD technology is far superior for the production of a semiconductor with an extremely uniform dopant concentration.

Silicon doped through NTD is therefore a commercially attractive application of RRs. The IAEA in 2012 issued a TECDOC dedicated to neutron transmutation doping of silicon [13].

4.3.2. Irradiation capacity

A RR aiming to offer the service of Si doping needs to provide one or more irradiation rigs able to process ingots with different diameters. The primary business in 2012 is based on ingot diameters of 5 and 6 inches, and the demand for the irradiation of ingots with a diameter of 8 inches is noticeable but not yet significant [12]. 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 the future. Corresponding test irradiations are underway at present, e.g., in Japan. The minimum acceptable height of the irradiation stack, which typically is made up of at least two 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, an irradiated Si storage area for at least of 1 tonne of Si, devices for cleaning of irradiated Si and instruments and trained staff for the performance of sensitive release measurements according to radioprotection regulations is absolutely necessary.

The current NTD market is dominated by 5 and, even more importantly, 6 inch ingots. 2.5 inch ingots and 3 inch ingots are rarely found in the current market. The share of 4 inch ingots has been decreasing drastically. Recently, the demand for irradiation of 8 inch ingots has grown, and its market share could expand in the future. Since the typical diameter of silicon ingots has become much larger, a large amount of silicon can be irradiated at an irradiation site. It may not be easy for many existing reactors to make new larger irradiation holes, but their inclusion in the design of new reactors is possible and will be necessary to satisfy the demand of the semiconductor industry. As found at OPAL, but also at FRM II and BR2 — all of them providing irradiation facilities for ingot diameters up to 8 inches — a large scale NTD facility may be possible while satisfying other needs upon a RR. After all, the construction of a large irradiation capacity for NTD could be profitable, though it is closely dependent on industrial demand for NTD-Si.

The annual capacity of a typical doping facility at a high flux reactor, i.e., a reactor with a thermal power >10 MW and an in-core neutron flux of $>10^{14}$ $cm^{-2}s^{-1}$, is between 10–15 tonnes per year [13].

4.3.3. Specifications

In addition to the increasing diameter of Si ingots to be irradiated it must be noted that an increasing demand for high target resistivity up to >1000 Ω·cm NTD-Si has arisen in the last few years. On the one hand this development is connected with an increasing capacity due to the achievability of high targeted resistivity during short irradiation times. On the other hand for this type of NTD-Si high quality neutron sources providing excellent thermalized neutron spectra are required because the effect of extended irradiation defects by fast neutrons on the electrical properties of a semiconductor is much more important at high resistivity.

The foremost advantage of NTD compared to other doping methods is the high uniformity of the final resistivity after doping a whole silicon ingot, which entitles NTD-Si to the claim of the best quality silicon for high power applications. Since the neutron flux in a reactor is not uniform, the overall uniformity in an ingot depends on the ingot size and irradiation technology. It is usually possible to control the neutron fluence very accurately, and therefore the resistivity target can be specified and accomplished within a very tight tolerance [14]. The accuracy of the target resistivity is a basic requirement for the doping process. Thus, the accuracy of doping combined with the overall uniformity will govern the quality of the product. The uniformity and accuracy criteria of NTD are determined in an individual contract between an irradiation site and a wafer company.

The physical volume of a batch of ingots is rather large, and the flux variation in such a volume is much more vital than the required uniformity in the target resistivity. Irradiation uniformity is expressed by radial and axial, or longitudinal, variations of the final resistivity after irradiation. Thus, radially and axially uniform irradiation is the prime target in the design and operation of an irradiation device. At the FRM-II reactor in Germany, the ingots were rotated during irradiation with a frequency of ~5 rpm to increase the radial homogeneity of doping [15]. The result was a maximum inhomogeneity of the flux profile of 12% along the cylinder axis; in contrast the radial inhomogeneity was below 3%. On the basis of these data the profile of a Ni absorber layer, the so-called liner, for the smoothening of the neutron flux density along the axis of the Si ingots was calculated using MCNP methods. For the final Si doping facility, this absorber layer was embedded into the Al tube surrounding the irradiation position by means of an injection moulding technique.

Neutrons used for NTD are mainly thermal neutrons, and a higher thermal neutron flux results in a shorter irradiation time. If the irradiation time is too short, however, an accurate irradiation is difficult unless the ingots are inserted into and withdrawn from the neutron field very rapidly. If the flux is too low, a very long irradiation time, which limits the practical application for NTD, results.

For a neutron flux of 10^{13} $cm^{-2}s^{-1}$, about 17 hours are needed to obtain 50 Ω·cm. When one hour of irradiation is applied, about 800 Ω·cm is a reasonable upper bound at a flux of 10^{13} $cm^{-2}s^{-1}$. In the case with a flux five times higher, the upper bound is about 160 Ω·cm. Low flux reactors with a thermal neutron flux approximately10^{12} $cm^{-2}s^{-1}$ can properly accommodate high resistivity targets. Since fast neutrons create extended charged lattice defects in a crystal, the fast neutron flux in the irradiation position must be as low as possible. Gamma rays are the major source of heat generation in the ingot, so the gamma ray flux should also be as low as possible, and the ingot must be sufficiently cooled during the irradiation.

The diameter of an irradiation hole should be large enough to accommodate an irradiation rig containing the ingots, coolant paths and online flux monitors. Because the NTD service charge is usually based on the number of irradiations or cycles, the irradiation of large volume ingots is profitable. However, loading and unloading of large ingots significantly distort the neutron flux at nearby experimental facilities and neutron detectors for reactor operation. Since silicon ingots are very brittle, careful design and operation of the ingot handling tool is required to preclude damaging ingots. Particular attention must be paid to the use of gloves during all handling procedures and to the cleanliness of all storage locations within and outside the reactor pool. Irradiated ingots must be cooled to reach the exemption level of residual activity, so a proper space is needed for cooling irradiated silicon. Contact to steel and other metals must be strictly avoided.

Irradiated ingots must be cooled to reach the exemption level of residual activity, so a proper space is needed to cool down the irradiated silicon. In addition, a cleaning facility, e.g. an ultrasonic bath connected to the radioactive waste water tanks of the reactor, is needed to remove potential contamination from the surface of the Si ingot with reactor pool water. Finally, for commercial irradiation services, systematic QA, traceability of the product and control measures are necessary. Many customers of NTD service require the certification of the irradiation facility according to the ISO 9001:2008 standard of the International Organization for Standardization (ISO) because they are urged by their customers to only cooperate with ISO 9001 certified subcontractors.

4.3.4. Market potentials

The worldwide demand for NTD increased rapidly up to the early 1990s. During the 1990s, the demand decreased due to the development of other competitive technologies and remained stagnant until the mid-2000s at about 100 t/year. Since then, however, NTD has been facing new circumstances. The demand for high power semiconductors may increase rapidly according to the swift increase of alternative energy technologies and much wider use of “green energy.” It is estimated that worldwide approximately 120–150 tonnes of silicon single crystals are doped in RRs every year with the irradiation cost on the order of US $70–100 per kg.

A very rough projection of NTD is as follows: In 2005, the worldwide production of new cars was about 60 million and could be more than 100 million in 2030 [13]. If 50% of new cars will contain hybrid, electric or fuel cell engines in 2030, then the number of new cars equipped with electric motors is assumed to be about 50 million. If one 6 inch NTD silicon wafer is used per car, since a silicon wafer requires about 1 mm thickness including the sawing part, NTD-Si of about 2000 tonnes per annum would be needed to satisfy this demand. It is not certain whether this future demand will be met by reactors. If the supply of NTD-Si is not sufficient, the industry may use another, likely more expensive, technology.

At any rate, since the pressure on industry from environment groups is becoming stronger, “green energy” technology could rapidly expand. Therefore, it is likely that the future demand for NTD will increase.

Opportunities for penetrating this market with reactor services are strongly based on the competitive efficiency of the RR facility. This includes applications of a reliable QA or quality control (QC) service ensuring aspects such as production of dopant uniformity axially and longitudinally; turn-around time, the time between delivery to the reactor and the return to the customer; reliability of supply; and of course the cost of the service; are maintained.

It is essential for the facility to interact with the customer prior to the establishment of a commercial contract. Customers have requirements on the resistivity target, often better than 4%, which sets a strong demand on the estimation of the neutron fluence.

Once the customer has confirmed that the required specifications have been met, the facility can develop its QC programme, e.g., one based on the relation between resistivity change and neutron fluence. This will be dependent upon the target material.

The development of annealing facilities and a subsequent end resistivity measuring ability is expensive and is often only possible if the related technology is shared by the customers.

4.4. Neutron activation analysis

4.4.1. General

Neutron activation analysis is a qualitative and quantitative analytical technique for the determination of elements, typically in trace amounts, in a variety of complex sample matrices. NAA is the most simple and the most widely used application of RRs [16–22]. Almost any reactor of a few tens of kilowatts and a neutron flux of at least 1×10^{11} $cm^{-2}\cdot s^{-1}$, as well as high power and 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 one of the main applications of RRs from a commercial point view, but it also can have a significant contribution to the social justification of the facility.

Based on information available through the IAEA RRDB [1] a rough estimate of the potential global capacity for commercial NAA services can be done:

— 229 RRs are operational worldwide as of December 2012;
— Half of them have claimed using NAA, therefore;
— A total of ~115 NAA laboratories can be realistically considered, taking into account also laboratories not directly affiliated to a nuclear reactor [1].

Assuming two counting facilities per laboratory and a processing capability of 10 samples/day, a laboratory may have a maximum annual capacity of analyzing 4000 samples/year. In practice, however, many laboratories run at only ~10% of this capacity.

4.4.2. Analytical characteristics

Although there are many situations in which NAA has on paper better analytical characteristics than other methods of elemental analysis, it is important to remain realistic in evaluating the role and possibilities of NAA. Therefore, the traditionally and below mentioned advantages of NAA are revisited in view of the alternatives available:

(i) NAA possesses sensitivity and applicability for minor and trace elements in a wide range of matrices, which applies equally well to atomic absorption spectrometry (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and even total reflection X ray fluorescence (TR-XRF).

(ii) NAA is conducted with a virtual absence of an analytical blank.

(iii) NAA offers relative freedom from matrix and interference effects, which is not always a need for renewed method validation.

(iv) NAA boasts a possibility to perform bulk analysis without dissolution; furthermore, NAA is the only existing technique for non-destructive bulk element analysis.

(v) High specificity based on the individual characteristics of the induced radionuclides is a remaining advantage of NAA.

(vi) INAA has a capability for multi-element determination, often allowing 30 to 40 elements to be determined in many matrices, which applies equally well or even better for ICP and in a lesser scale to TR-XRF;

(vii) NAA possesses an inherent potential for accuracy compared to other analytical techniques, and since the theoretical basis of NAA is well understood, a complete uncertainty budget can be made, which is a remaining advantage of NAA;

(viii) The totally independent nature of the method as a nuclear based property favors NAA in contrast to the electronic nature of most other analytical techniques;

(ix) The isotopic basis of the method offers a choice of analytically independent routes for element determination, and since different nuclides of one element can be determined either simultaneously or via different protocols, NAA has a self-verifying character;

(x) In cases where the induced radionuclides of trace elements are masked by matrix activity, radiochemical separation provides interference free detection limits close to the theoretical ones. In the radiochemical mode of NAA (RNAA), the technique has other advantageous features. However, the laborious activities related to RNAA must be compared to the simplicity of, e.g., ICP, which offers often comparable or even better detection limits;

(xi) Trace and ultra trace (radio-) chemistry can be performed under controlled conditions by using inactive carrier additions, while alternatively, stable isotope tracer techniques can be followed if ICP-MS is available; and

(xii) The chemical yield of the separation can be obtained by simply using carrier budgeting or the radiotracer method, a remaining advantage of NAA.

4.4.3. Market potential

NAA is marketed on the basis of those analytical characteristics that favorably differentiate the technique from others and that are extensively described in associated literature [18]. Niches exist for:

- Determination of the total bulk elemental composition of materials difficult to dissolve completely or in which elements may be lost during dissolution;
- Precious samples that must be analyzed non-destructively;
- Studies involving samples for which other methods of analysis have difficulties in the calibration step due to chemical matrix effects. This applies particularly to studies in which the matrix composition varies considerably in an unpredictable way, or for which no matrix matching calibrants exist;
- Samples in which the trace element levels are so low that contamination or losses may occur easily during the sample dissolution or digestion step;
- Analyses requiring a high degree of accuracy and, even more, reliability to ensure full comparability of data obtained over a long period of time;

— Samples with a high degree of inhomogeneity, requiring the processing of a relatively large analytical portion to ensure representativeness; and
— Samples in which the element concentration among samples may vary over several orders of magnitude; here the linearity of NAA is of importance.

There is a clear demand for such NAA services from various industries. Industrial customers have requirements which must be met not only for technical contents but also for all other logistics such as on time delivery and proper non-disclosure agreements. For a successful commercial opportunity an infrastructure must be built to have business-like interaction between the service provider and the industry. Industrial customers require priority, confidentiality, and on time delivery. Service providers must show long term commitment so that industrial customer can rely and plan future manufacturing.

In this regard an operational quality system and formal accreditation are of particular advantage. Service laboratories, in many cases, must demonstrate to their customers that they are working according to internationally accepted standards such as ISO/IEC 17025:2005. In recent years much progress has been made to assist nuclear analytical laboratories in their attempt to comply with these requirements [21, 23].

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, among others. In addition, NAA has a role in 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 can be applied to the following areas:

(i) **Mineral characterization and in geological sciences:** Irradiation of mining samples to detect metal traces with high trueness and precision is useful for identifying veins in metal mining and in surveys, determining the abundance of elements in different areas, analyzing rocks and minerals and quantifying impurities in crude oil through the on-line method.

(ii) **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.

(iii) **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 a capability to identify microelements contained in soil, river and sea bed sand, and environmental and foodstuff samples.

(iv) **In biology and medicine:** The determination of trace elements in different human tissues both normal and with pathologies can be useful for research, diagnosis and therapy purposes, kinetic studies on metabolism and element distribution in the human body. For each it is important not only to determine the concentration of the element but also its exchange speed among different organs.

(v) **Heavy industry metal characterization and material sciences:** NAA is significant in the QA process within heavy industry, since heavy material samples are analyzed to identify isotope concentrations, guarantee their origin and verify the effects 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.

(vi) **Forensic science** is another important area of application of NAA.

Some specific examples of industrial opportunities are:

- Analysis of trace oxygen in steel, noting that direct measurement of oxygen is only provided by (14 MeV, non-RR based) NAA, and impurities during petroleum processing;
- Determination of chlorine in steel and in nuclear materials;
- Hydrogen analysis in the Ti metal aerospace industry by prompt gamma NAA;
- Hydrogen determination in energy storage devices;
- Halogens and metals in the polymer and rubber industry can be uniquely addressed by NAA. For example, the Dow Chemical Company has installed a research reactor for their own use at their Midland manufacturing facility in Michigan; Dutch State Mines has its own on-site NAA laboratory for similar types of assays;
- Elemental analysis for industries producing ceramics, graphite, industrial diamonds and other highly refractory or insoluble materials like AlN, Si_3N_4, W;
- Impurities in emerging nanomaterials, e.g., carbon nano tubes;
- Bulk analysis of silicon wafers; Si_3N_4; and SiC, quartz, or graphite liners. The need for such analysis in the semiconductor industry is a daily phenomenon and currently not being met adequately;
- Determination of ^{129}I in environmental samples;
- Dual energy gamma ray metering for multi-phase flow in the petroleum industry;
- Analysis of precious metals in minerals, catalysts and wastes;
- Similarly, NAA can be interesting for governmental agencies for regulatory purposes and health care;
- Quality testing of wine;
- Forensic testing of hair;
- Testing for Br in neonatal blood;
- Determination of trace elements in air filters;
- Determination of U in ashed tissues;
- Testing for organochlorines in fisheries samples; and
- Determination of iodine in biological materials, especially food.

4.4.4. Radiochemical NAA

Chemical separations are often employed in conjunction with NAA and may be applied to separate the element of interest from the matrix prior to the irradiation. Since an interference free test portion is thus obtained, any other analytical technique may be used as well. Sometimes NAA is preferred because of the technique’s superior sensitivity, and the method can be classified as pre-concentration NAA. In the case of either replacement of the element of interest or its combination with another element that can be determined by NAA with better sensitivity, the method is named derivate NAA.

4.4.5. Delayed neutron counting

Delayed neutron counting is a form of NAA used to determine the uranium content in samples of different origin, varying from uranium ore samples supplied by mining companies to biological samples.

When uranium or thorium is irradiated with neutrons, fission may occur resulting in fission products. About 200 fission products of ^{235}U are known, most of them beta emitters. Some of the short half-life ($T_{1/2}$< 1 min) fission products have an excited state with a potential energy larger than the binding energy of a neutron; thus, they decay under emission of neutrons. The delayed neutrons have an average energy of 0.5 eV, and they form the basis of a technique for the highly specific detection of fissionable material [24]. DNC is usually only applied for measurement of uranium in large batches of samples, e.g., for mineral exploration or monitoring programs. Since short half-life fission products are involved, irradiation and counting times can be kept short, typically 1 min each. Sample sizes are in the 1–10 gram range, and a fast pneumatic transfer system is required, preferably with a sample changer. Detection of the neutrons is done using BF_3 or ^3He detectors, usually in an annular array around the sample, surrounded by paraffin as a moderator for the epithermal neutrons. The entire facility must be automated for rapid processing of large batches. The neutron count data are automatically input into a computer programme that calculates the natural uranium content in the sample.

The system can easily be calibrated, and the only interferences to account for are the presence of thorium and oxygen (^{17}O (n,p)^{17}N) in the sample and sample container.

Detection limits that can be achieved by DNC depend, analogue to conventional NAA, on available neutron flux, sample mass, efficiency of the detector system and irradiation, and the decay and counting time. Values have been reported varying from 5 μg U for a 25 g urine sample at 10^{13} $cm^{-2}s^{-1}$ [25] to 0.1 μg U in a 1 g soil sample [26].

Typically, the facility can be operated at any thermal neutron flux >10^{12} $cm^{-2}s^{-1}$. 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.

4.4.6. Prompt gamma (neutron) activation analysis

Prompt gamma neutron activation analysis is based on the measurement of gamma rays emitted promptly upon the capture of a neutron by an atom in a sample that may be solid or fluid. PGNAA is enjoying increasing utilization, limited only by the scarcity of suitable neutron beams. Typical applications include the analysis of gram sized or smaller samples in geological, atmospheric, archaeological and modern materials sciences.

PGNAA is especially valuable as a non-destructive nuclear method in the measurement of elements that do not form neutron capture products with delayed gamma ray emissions. Furthermore, the elemental coverage of PGNAA complements that of conventional or delayed INAA.

The list of measurable elements emphasizes the low Z and high abundance elements in organic and geological materials and high cross-section elements like B, Cd, Sm and Gd. The analysis for hydrogen and boron is especially important because of the paucity of other reliable analytical techniques for trace levels of these elements. PGNAA is extremely sensitive for the quantitative determination of B compared with destructive chemical techniques, particularly since boron is such an important element over a wide range of applications from meteorites to human tissue [27–30]. Together PGNAA and INAA can measure all elements except oxygen in most common materials. Conveniently, in silicate rocks and similar oxidized materials, the completeness of the analysis can be tested by expressing the elements as oxides and comparing their sum with 100% [31]. Because nearly every neutron capture is a (n,γ) reaction, the yield of prompt gamma rays per neutron is greater than that of delayed gammas [32]. Unfortunately, PGNAA has usually poorer sensitivity compared to INAA because the neutron flux is some five orders of magnitude lower in an external reactor beam than an irradiation position near the core. [33]

The technique has applications in geological, atmospheric, medical and environmental fields. A PGNAA instrument consists of a source of neutrons, a collimating thermal or cold beam tube to shape and direct a beam of neutrons with a flux[3] greater than 10^8 cm^{-2} s^{-1} over an area of several cm^2 onto a sample, a shutter to turn the beam on and off, a target assembly to position the sample reproducibly in the neutron beam, an n-type Ge semiconductor detector, a beam stop to absorb the neutrons not absorbed by the sample, and shielding to protect the detector and personnel from neutron and gamma radiation. Each of these components will be considered in turn.

A tangential tube is preferred in comparison to a radial tube for a better thermal/fast flux ratio and thus improved signal/background ratio. The most effective PGNAA systems are operated with neutrons provided by a neutron guide, because guides, particularly bent guides, deliver a much cleaner flux to the sample, creating the improved signal/noise ratio. Guides also facilitate physical separation of the PGNAA spectrometer from the reactor and from other instruments that contribute to the gamma background. Curved guides are often used to avoid direct sight of neutron sources that emit also fast neutrons and gamma radiation, since these components are not reflected at all. The curvature radius is typically large, varying from 1000–5000 m [35]. In addition, a Compton suppression system is a desirable option to surround the Ge detector, although this is not a necessity with larger Ge detectors.

Typical examples include the detection of boron in blood and tissue samples of patients when requested by the boron neutron capture therapy and the detection of pollutants in air filters for environmental purposes.

4.5. Neutron beam analysis

An incident neutron beam falling onto a given sample may interact with it in different ways, with probabilities determined by the respective cross-sections. As a result of an interaction a neutron may be absorbed, scattered or transmitted by the sample material.

Various kinds of neutron techniques are currently available for material science applications at reactors [7, 36–38]. Radiography and neutron tomography using thermal and fast neutron instruments are applied for determining structures of novel materials, materials diffractometers for internal stresses and textures, neutron reflectometers for characterising surfaces and multi-layers of soft and magnetic matter, as well as inelastic spectrometers to follow the internal dynamics of the atoms and molecules.

Neutron diffraction experiments are performed on materials with the aim of correlating the structure with some physical property. This is particularly important for new materials with

[3] Published fluence rates (or fluxes) of reactor beams that have been used for PGNAA range from 10^5 cm^{-2} $s^{-1}$to over 10^{10} cm^{-2} s^{-1}, although 10^7–10^8 $cm^{-2}s^{-1}$ is most common [34].

eventually completely new functional properties. Combined with a high flux neutron source, new high intensity powder diffractometers are capable of performing very rapid, real time, in situ measurements of chemical and metallurgical processes, e.g., those involved in synthesising new materials.

In a SANS experiment, a monochromatic focused beam is scattered by inhomogeneities in the sample. This is a highly versatile technique that has been applied to investigations on a wide range of materials, including emulsions, polymers, colloids, superconductors, porous media, geological samples, alloys, ceramics and biological molecules.

A neutron reflectometer is an instrument dedicated to the study of interfaces by neutron reflection. It is particularly useful for studying surfaces, buried interfaces, complex fluids, magnetic films, multi-layered structures and processes that occur at surfaces and interfaces. A polarizer and a flipper can be installed in the reflectometer in order to perform polarised neutron measurements. Magnetic nanoscale objects like magnetic particles, clusters and vortices can also be studied with the use of polarised neutron beams.

The powerful neutron inelastic techniques enable determinations of the strength, the characteristics of the interatomic forces and magnetic coupling in a material. This type of knowledge is relevant to the understanding of the nature of diffusion of hydrogen in materials such as in battery technology, the atomic origin of thermoelectricity, or the magnetic coupling responsible for the superconductivity in ceramic cuprates.

From the point of view of engineering material science, it is not only diffraction or scattering experiments that are useful to provide important structural information. Transmission experiments, on which neutron radiography and tomography are based, have also become very powerful tools to evaluate large components under operational conditions.

There are several neutron beam facilities at low power reactors as well as reactor facilities in developing countries that are underutilized. Two major causes for this have been identified; one is staff related, and the other is hardware related.

The first major obstacle has been the absence of links between the reactor centres and the scientific community. Some countries have focused on the commissioning and operation of the reactor itself rather than on any beam applications such as the design and installation of scattering instruments. The staff are fully involved with the reactor operation and not particularly concerned with instrumentation or reactor users. In other cases, staff are mostly active in instrument design, development and improvement without having science based utilization of the instrument.

Secondly, in relation to hardware, instruments for neutron beam techniques cannot be purchased ‘off the shelf,’ and in-house development requires ample expertise in neutron physics, shielding optimization and instrument design, together with skilled workshops. The main impediment to successful material structure experiments at a low or medium power RR is the amount of time necessary to collect data. Reactors that have operating schedules of only a few hours per day are not attractive for developing, implementing and offering services with neutron beam techniques.

4.5.1. Neutron radiography/tomography

Neutron radiography is a powerful tool for non-destructive testing of materials that has found numerous applications in industry and in material research as well [37]. A beam of neutrons falls on the sample and, after passing through the sample, leaves the sample image on a photographic plate or on a detector. The neutrons interact with the nuclei of the atoms that compose the sample, and the absorption and scattering properties of the contained elements make it possible to produce images of components containing light elements like hydrogen beneath a matrix of metallic elements such as lead or bismuth, which cannot be easily done with conventional X ray radiography. Exploiting this property, neutron radiography has been used in applications requiring the identification of light materials inside solid samples. Whereas 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 metal parts

In the past, the "picture" was registered on a neutron sensitive foil typically composed of Gd or Dy on which photons produced from a converter foil via neutron interaction activated a film. 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 charge coupled device (CCD) cameras with a scintillator screen as the primary neutron to light converter. Other methods, amorphous silicon arrays and micro-strip gas counters, are not yet completely optimized for neutron imaging but have a high potential as detectors in radiography and in neutron scattering experiments as well. Recorded two dimensional images are reconstructed using sophisticated image reconstruction software, leading to three dimensional information of the inspected object or sample, which is the basis for computed neutron tomography.

Neutron radiography has found its greatest applications in the examination of nuclear fuels, explosives, electronic components and engine turbines blades. The technique has also been introduced in new branches such as fuel cell research, the study of objects from cultural heritage, geoscience and soil physics. The extension of applications into new domains depends very much on the performance of beam lines, research infrastructure and access conditions for external users. Examples of applications are corrosion studies in aluminium for the aircraft industry; behaviour of moisture in building materials; and distribution of hydrogen, oil or lubricants in mechanical equipment, including fuel cells and car engines.

Further development includes three dimensional imaging methods such as tomography, the exploitation of different neutron energies in the impinging beam to gain additional information and real time analysis of systems including fluid flow or moving components.

The measurement result depends strongly on the neutron source properties and the detection system used. Neutron radiography is even possible at low flux reactors. With a stronger neutron flux available at medium and high flux reactors, neutron tomography offering spatial resolution down to 10–20 µm becomes feasible. Additionally, contrast enhancements based on the application of a monochromatic neutron beam, e.g., Bragg edges, have been successfully demonstrated.

Detection systems have taken a big jump from conventional photographic film to digital real time imaging.

The following factors need special attention in the design of a neutron radiography facility:

(i) **Gamma radiation reduction:** Filtering of gamma radiations is necessary especially if the facility is built using a radial beam ports. Bismuth and lead are good candidates as filters, with a preference for bismuth since its neutron absorption is less. A single crystal helps in avoiding Bragg cut off edges in the transmitted neutron spectrum. The optimum size and neutron to gamma flux ratio need to be resolved using simulations for the given reactor parameters. Typically a single crystal of bismuth of 10 cm in length is used.

(ii) **Shielding:** Shielding against scattered neutron and gamma radiation is indispensable. Often a sandwich of borated polyethylene and lead is used. Concrete is also applied because it is less expensive and easier to apply in any shape depending on the availability of space. The use of materials that can emit capture gamma radiation should be avoided.

(iii) **Beam catcher:** The beam catcher should be designed in a manner in which it absorbs the beam transmitted through the sample without back scattering. Boron carbide in a sealed aluminium box works well.

(iv) **Imaging system:** The digital radiography imaging system can consist of a LiF+ZnS scintillator, a front coated mirror and a cooled CCD with appropriate acquisition software. Such systems are quite common in many labs worldwide and commercially available. The specification of the CCD depends upon the resolution and the dynamic range required. Ideally a large area CCD with 1000×1000 matrix should be used with cooling typically to around –30°C. However, a low cost system can also be designed using 512×512 matrixes with around 10–13 micron pixels.

4.5.2. Small angle neutron scattering

For medium and high flux reactors equipped with a cold neutron source, SANS 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 in which SANS instruments are funded and operated directly by industry.

4.5.3. Neutron diffraction for residual stress and texture analysis

Today there is a strong need for the development of non-destructive testing tools for polymers and especially composites [39]. The latter, like fiber reinforced polymers and metal matrix composites are microstructured materials that exhibit a much more complex fatigue and degradation behaviour than steels, which can be treated like a continuum. For these types of materials the currently existing models are still not developed far enough to enable reliable lifetime predictions of components, even assuming a completely known component structure, stress distribution, pore distribution, etc. Thus to avoid very conservative decisions the effects of defects must be studied in detail.

Non-destructive testing plays a large role in monitoring within industrial production process as well as for component maintenance to prove the structural integrity and to ensure reliability and safety. Neutron diffraction based residual stress determination is the only quantitative method to evaluate the averaged three dimensional strain tensor within the sampling volume defined by the instrumental setup. Structural health monitoring systems must be mentioned in addition. 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 non-destructive testing tools. This results in an enhanced reliability of lifetime predictions, enabling less conservative QC decisions without reducing the degree of safety. Finally the appropriate use of neutrons as a reference method can be highly cost effective for commercial users. However, it should not be underestimated that customers may dislike neutron diffraction because of its immobility, slowness and costs of a method that is of secondary importance. Still, the major focus lies on reliability and availability of quantitative results together with adequate spatial resolution. Here neutron and synchrotron methods are playing the key role for the determination of urgently needed reference values.

Typical samples successfully investigated by neutron diffraction to determine local stress states are crankshafts, pistons, turbine blades and wheels, impellers, shot peened components and welds. A special type of truck crankshaft has been suffering from rare but remarkable failure events occasionally. X rays applied after cutting equivalent samples at the region of interest did not show any evidence for the responsibility of failure being upon residual stresses caused by the induction hardening process. Using neutron diffraction at the BER-II reactor in Berlin, absolute values of the “real” stress states found in the region of the oil channel surface have been approximately three times higher than the results determined by the in-house X ray experiments.

Titanium based alloys do not reveal deep insights into the sample’s three dimensional stress distribution due to titanium’s strong incoherent scattering background.

4.5.4. Neutron reflectometry and other neutron techniques

Neutron triple axis spectrometers, filter detector spectrometers and quasi-elastic neutron spectrometers have been used to study several dynamical processes like phonon dispersions, magnetic excitations, rotational and translational diffusion in molecular systems, etc. [40]. The lattice dynamics of several geologically important minerals, available as natural single crystals, have been investigated by triple axis measurements.

The following has been highlighted as an important conclusion for neutron beam applications:

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

(ii) In order to optimize the instrumentation according to the needs of the market, a broad interface with 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.

4.6. Material and 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). 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 some projects aligned towards the development of emerging Generation IV reactors. Support to current generation reactor operation and deployment has resulted in programmes addressing irradiation damage in structural materials for ageing management through safety analysis and life extension and fuel irradiations to enhance fuel cycle economy and safety. The main advantage in the use of RRs 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 [41].

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; and
- The availability of the facilities irradiation and post irradiation examination facilities at the same location or the construction of an international network.

Research reactors 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 than irradiations of materials for current generation reactors. Enhancement of international accessibility and utilization in order to avoid unnecessary duplication and increase complementary studies among RRs was strongly recommended by the meeting participants.

In all cases, irradiation facilities, rigs and loops all must be tailored to the application and reactor design.

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; and
- Irradiation tests of reactor materials and high temperature irradiation tests.

4.7. Gemstone colour enhancement

There is an opportunity to use RRs to enhance the quality of and, thus, add value to, gemstones. Gemstones may be irradiated with neutrons to improve their properties, e.g., a change to a more desirable colour, in order to increase their demand and monetary value [42]. A few gemstones such as topaz and diamond can reach 30 times their natural value thanks to neutron irradiation. One of the more significant commercial neutron irradiation activities currently being performed at RRs is for the coloration of topaz. Due to commercial sensitivity, there is an understandable reluctance amongst those performing irradiations to disclose the specific details of their process, in particular for both NTD and gemstone applications. A combination of gamma radiation and high energy electrons along with neutron irradiation can increase the values of more variety of gems. The application requires substantial R&D and experience prior to commercialization. In addition, there are some difficulties associated with gemstone coloration activities that should be heeded.

The world of gemstones and the world of reactor management, operation and utilisation are culturally very different. The market for irradiated gemstones is volatile and difficult to assess, as it is dependent on the size and the colour of stones currently in fashion. This often makes the behaviour of the gem trader also appear to be whimsical. In addition, the operating schedule for the RR and the time required for the irradiation and processing of stones is often incompatible with the needs of the trader.

The decay times involved in the radiological cooling of irradiated gemstones is often quite long, resulting in a trader's investment risk in the virgin material, particularly when compared to the gem trade's cultural time frame. The reactor facility bears an investment risk in both the irradiation devices and the development of the measuring equipment. The facility is also dependent on the delivery of good quality virgin material so that it is not left with a large quantity of material that is useless because of long lived activation products.

The stones are typically batch irradiated in containers; at one facility a batch consists of about 2 kg of stones. Since only fast neutron irradiations are desired, the containers or the irradiation facility are often shielded with cadmium or boron. Because the temperature during irradiation must be controlled, some method of cooling the stones is also necessary

At the end of the irradiation period, a storage facility must be available for the stones until their radioactivity has decayed below the specified release limit. The storage time period is strongly dependent on the original characteristics of the stones. It has been experienced in some cases that it was possible to release 70% of the stones after 2 months and only after 8 months had 80% of the stones been released.

Because of market forces, it is desirable to release the stones as soon as possible. This requires frequent determinations of the radioactivity of the stones and predictions of a release date. Automatic handling and activity measuring robots can be used to perform these periodic measurements of the stones.

In some countries, the radioactivity limits for releasing the stones have become nuclide specific. This will require the use of a multi-channel analyser as well as a system for determining beta emissions from each stone prior to its release for transport. Considering safety aspects, each irradiated grain product should contain a radiation residue less than the acceptable value of 2 nCi/g. State regulations related to gemstone irradiation varies from country to country, and in particular, many within the EU prohibit commercialization of irradiated gemstones.

4.8. Boron neutron capture therapy

Boron neutron capture therapy is still a controversial approach for treatment of certain melanomas and brain tumours. The principle of BNCT is well established: with boron atoms incorporated specifically in the tumours, irradiation by thermal neutrons will cause the $^{10}B(n,\alpha)^{7}Li$ reaction. The alpha particle is highly ionizing and has a range in tissue about equal to the diameter of a cell**.** If the conditions are right, then the tumour dose is much higher than that of the rest of the surrounding tissue, resulting in subsequent preferential eradication of the tumour's cells [43].

The controversy in the medical community results from the difficulties in producing boron carrying drugs that specifically accumulate in the tissue or pass the blood–brain barrier but not in healthy tissue, and that a relatively small number of patients have been treated without a significant benefit.

Boron neutron capture therapy facilities consist of an epithermal (0.5 eV–10 keV) neutron beam of ~10^8–10^9 $cm^{-2}s^{-1}$. The epithermal neutrons are further thermalized in the overlying tissue before reaching the tumour. The beam must be further optimized by minimizing the thermal neutron, fast neutron and gamma radiation components while keeping the epithermal neutron fluence rate as high as possible. This all is attained by using appropriate filtering. Filtering transmits neutrons of the desired energy while blocking those of other energies. In general though, because filtering is more wasteful with respect to neutrons, a much higher original source flux and therefore reactor power is needed.

Reactors in the 100 kW to 1 MW range have been especially adapted for this task, for example, the Mushashi Institute in Japan, VTT Technical Research Centre in Finland, and Massachusetts Institute of Technology in the 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 (Germany) and some RRs in Russia, Argentina and China have also developed or designed such trial treatment facilities. In addition, it has been demonstrated that even a quite low power (~10 kW) fast reactor, if planned and designed from the very beginning, can produce epithermal neutrons at desired intensity levels. Most facilities must be equipped with shutters in order to stop the beam without shutting down the reactor.

The beam must emerge into a well shielded treatment room that allows for observation of the patient during treatment, and the reactor control and safety system must be expanded to include an interlocked system for the BNCT facility.

New reactors frequently incorporate facilities to enable BNCT capability in their design. Most existing reactors, however, were designed before the concept of BNCT and generally have not done so. The ease at which an existing reactor can be modified will be very dependent on the facility design. Since BNCT is still in the research phase and since the efficacy of the treatment is still unproven, many people believe that there are sufficient facilities currently available for the necessary studies and additional facilities are not needed at this point.

In addition, a medical facility is needed near the reactor premises or even integrated in the reactor building. BNCT is a medical procedure that is administered under the supervision of a physician and a medical staff associated with a nearby hospital. BNCT requires the development of medical treatment protocols that sometimes require the approval of a governmental health agency in addition to a nuclear regulatory body. Medical liability insurance may be a requirement for the RR facility.

Finally, even if BNCT eventually becomes a viable treatment option, a market or needs analysis should be performed to determine the number of potential candidates that would be available for treatment. An example of a simplified approach to the study follows[4].

5. CONSTRAINTS AND OBSTACLES FOR COMMERCIAL SERVICES

5.1. Business plan

Organizations providing services and products of RRs are faced with a set of constraints and obstacles that may be new to them. Providing services and products to third parties, whether fully paid for or not, may require a change in the mindset of personnel and organizations from science oriented towards a focus on customers. The consequences of such a service approach must be outlined within the context of the original mission of the organization. As an example, whereas scientists are used to producing results at best measurement capabilities, services to customers may require a 'good is good enough' approach. Priorities may be set for the use of instruments, manpower allocation and even reactor schedule; investments may be needed for improvement of facilities. In some instances the organization is ready for providing services and products, but customers are missing.

A business plan is therefore almost indispensable. It contributes to transparency on the objectives, necessary steps to be taken and expected benefits of providing services and products.

The business plan [45] should start with the objective for providing services as mentioned in Chapter 2, which typically entails an increase in the community of stakeholders and users or generation of extra budgetary income. A mix of these two is also possible and should be an ultimate goal. Secondly, the organization may wish to commit itself to attaining a quantifiable performance such as a number of users, a number of reactor operating hours or a generated income after a certain number of years. At this stage it is important to realize that there are only a few reactors worldwide at which income from services is equivalent to a significant part, e.g., >20–30%, of the annual running costs of the facility.

The business plan furthermore should include a strengths–weaknesses–opportunities–threats (SWOT) assessment of the reactor's potential and a market orientation.

5.1.1. Reactor operation and management

A reliable and long term schedule of RR operation and guaranteed on time access to requested services are expected by customers, especially for radioisotope production. Obvious contradictions as well as major interferences like necessary shutdowns for loading and unloading irradiation goods must be identified and addressed with respect to their acceptability by all end users of the facility. RR ageing related issues, e.g., staff, RR related infrastructure and auxiliary equipment, should be reflected in the utilization strategy and risk analysis, including possible remedies.

[4] The Central Brain Tumor Registry of the United States estimates that 3.2 of 100 000 people develop glioblastoma multiforme (GBM) in the United States each year. The largest single age group diagnosed with this cancer is ages 65 to 74, followed by ages 75 and up, such that approximately 2/3 of diagnosed patients are over age 65 [44]. If the incidence rate were assumed to be the same as in the United States , there would be about 960 cases per year in a country that has a population of 30 000 000. Because the expected lifetime in some countries is lower than in the United States, the incident rate should be lower. In addition, for a country with a widely dispersed rural population, some diagnoses will be missed. Based on this, the number of patients in such a country could be well below the 960 calculated.

A balance of beam time allocation between science and industrial clients must be formally established. As an example, unless a multi-user shared beam facility is firmly established, an organization with external customers may decide to allocate not more than 50% of the available neutron beam time in order to have sufficient capacity left for research and methodological R&D. Similar considerations apply to the allocation of NAA facilities.

The organization should anticipate implementing management systems that comply with international standards like ISO 9001:2008, ISO/IEC17025:2005 and the Good Manufacturing Practises of the Organisation for Economic Co-operation and Development (OECD-GMP). Such a QM system can be implemented in any laboratory irrespective of its size and number of staff, and accreditation can be obtained within 2–3 years as has been demonstrated via several IAEA Technical Cooperation projects [46]. Certification or accreditation thereof may be a precondition for success in market penetration. These credentials contribute by creating confidence in the service of the RR, and the running costs of an accredited quality system can be incorporated in the costs of the service.

Research reactor facilities have been challenged to establish a self-stabilized and self-controlled service system that is based on reinvestment of the generated income as well as some guaranteed subsidies by the operating institution. At least some return of revenues is needed to compensate for incidental running costs for providing the service.

Preferably permanent staff should be in charge of the service experiments due to the importance of continuous quality of the deliverables.

Regional, international and sometimes worldwide cooperation is unavoidable as has already been realized in the cases 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. Coordination between different production facilities to ensure backup solutions during prolonged outages and overhauls is vital for regular isotope production.

The types of radioisotopes intended for production and their induced radioactivity may have specific consequences for infrastructure and logistics such as means for loading capacities for the irradiated samples, unloading equipment particularly during reactor operation, availability of hot cells, quality control of the irradiated materials and a sufficient number of well trained and experienced staff. Procurement obstacles for spare parts and consumables like vials, reference materials and liquid scintillation cocktails must be overcome.

For commercial industrial applications, the continuous observation of the market is of the highest importance. Customer feedback should be actively sought. A common database on the capabilities of various RR techniques and products needs to be created and updated continuously.

Automation and standardization of calibration and measurement procedures, including associated documentation, boosts reliability and repeatability and thus the overall efficiency of facility use, which may also improve with the adoption of industrial quality standards and efficient facility pooling in order to enable fast and flexible access to the facilities.

5.1.2. Positioning

The following regional supply situations have been identified:

(i) There is only one RR service within the country, and access to facilities in neighbouring countries or regions is not possible or desirable. There is essentially no competition. The RR then has a monopoly position and staff and owners should take precautions that this will not engender arrogance.

(ii) There are other similar RR facilities within the country or easy accessible reactors in neighbouring countries. Opportunities should be sought on the basis of uniqueness of facilities, expertise and quality of the team, customer relations, turnaround time and costs. Alternatively, strategic alliances with these reactors could be an opportunity to strengthen the group's market position versus institutions with competing techniques. IAEA stimulated RR networks and coalitions have demonstrated some benefits regionally and to the constituent institutes [4].

(iii) Techniques are available with characteristics to solve an analytical problem. Strengths and weaknesses of the nuclear analytical technique and its competitors must be evaluated.

5.1.3. Organization of services

Commercial services of RR usually begin as a side activity of a scientific department or the reactor operating group. However, once the activity grows, some staff members may wish to create a separate specialized commercial business unit. Sometimes revenue generating services receive a higher priority than doing research, and conflicts of interest occur. Scientists may be less willing to ask their colleagues for full payment for services in view of the impact upon their personal relationship. In addition, the administration, marketing and maintenance of a customer network may become difficult to combine with the prime task of performing scientific work.

There may be some objections against fully separating science and service such as a detrimental impact on the scientific network or the possible loss of direct revenues. Some flexibility with priorities of access to facilities, ranking of experiments, discounts, etc., should be agreed upon by all staff members. An additional problem with separate business units might arise in staffing, particularly in finding the right persons that are able to conduct commercial communication but also align the customer's request to the characteristics of the facilities and their performance.

A costs analysis and price strategy must be made. Many models for costs analysis exist, and the organization may seek external assistance for this. An estimation of reactor costs, or even the cost per neutron, can be made on the basis of the annual reactor running costs, available operating hours, average capacity available for the service and total number of types of services provided. The price to be charged depends on the overall strategy, which can be cost effective and non-profit, profit oriented, or accepting losses depending on market penetration or the prioritization of stakeholder building. Price settings may also depend on prices set by international competitors, either reactor based or those using alternative techniques, and even by an estimate of the economic benefits of the services. An organization may decide to offer prices lower than the actual costs depending on market penetration or if a number of end users is more important than full sustainability, since the number of end users may contribute to the visibility of the organization. As such, for instance, the reactor costs may be dropped altogether, which is often done, and justified based on the availability of the reactor and neutrons. It should also be noted that some customers may interpret cheap tariffs as unprofessional.

In addition, if an organization provides different services and products, the profits of one activity may at least partly cover the losses of another. Sometimes also governmental organizations and universities are forced to operate on a non-profit basis.

5.1.4. Customers

Customers may come from industries such as mining or agriculture, trade companies including customs agencies, governmental agencies, medical centres, universities and research institutions. Each of these parties may have specific requirements with respect to turn around time as well as the number of measurements to be done, the ease of measurement and willingness to pay. As an example, industry usually does not quarrel about costs of analyses, but the need for short turn-around times may present some difficulties. Governmental agencies may generate a continuous flow of samples to be measured, but for nuclear centres that receive regular government support, they may argue that analyses should be done for free.

Customers often have an entirely different perception of what the nuclear technique can offer. They often apply for the use of the nuclear technique when all other techniques have failed. Its strong and weak points are balanced against the 'in house' techniques and the disadvantage of contracting out. When solicited, the views of outsiders help the organization to understand the potentials of various techniques to provide scientific services.

Reliability in service provision does not depend on analytical quality only; it equally depends on the availability of facilities. For instance, an underestimated problem in NAA remains the absence of automation, which limits tremendously the analytical capacity. Most NAA laboratories have only one or two detectors, and commercial sample changers are considered very expensive. Laboratories are therefore not equipped to handle simultaneous requests for analyses. Capacity is limited by time consuming data handling that also stems from a lack of associated automation.

The customer expects that the analysis can be reproduced and eventually that the laboratory can defend its results in courts if necessary. The importance of QA/QC programmes is abundantly clear [21, 46].

5.1.5. Contacting customers

The market orientation in a business plan should also include a marketing strategy of how to inform the markets about the reactor's potential and how to attract customers. There are several methods to consider, depending on the level of experience in providing services in the organization.

Personal communication relating the existence of the reactor and its service potential can be done at several levels:

— Vís-á-vís a customer already known or a specific client or group in industry, a governmental institution or a university;
— Providing a seminar at targeted groups in a university or research institute for personal communication with potential customers; and
— Providing presentations on the reactor’s potential at conferences, seminars or meetings on targeted applied fields, e.g., mining, materials science and nuclear medicine.

Such presentations require substantial preparation to anticipate questions related to product specifications, sensitivities, turn-around time and prices, among other topics. A brochure describing the RR and its services must be available for general distribution. Brochures should be balanced in scientific content with an absence of jargon but precision regarding services to be offered. Technical details of instruments or facilities should be communicated separately if requested once interest has been established. An organization may seek professional assistance in developing a brochure.

Another approach in informing the market about the existence of the reactor’s services is by different forms of advertising such as:

— Contributions to technical journals in the targeted fields of science;
— Direct mail with follow up telephone contact; and
— A booth presentation at exhibitions, fairs, etc.

Scientists may face a difficult task in contacting their customers. In many cases, the customer is not knowledgeable in the scientist’s jargon and terms such as neutron flux, neutron energy and cross sections, which may be common in the nuclear field but hardly relevant to the customer. Training in commercial communication and so called “elevator pitches” is therefore a valuable investment for the marketing of the services.

6. CONCLUSIONS

Both the reduction of budgets for research and development and the underutilization of expensive facilities such as nuclear RRs set demands upon the creativity of managers and scientists implementing an infrastructure for routine service activities and integrating this smoothly with normal scientific research.

There are great opportunities for RRs to offer commercially nuclear training services to potential customers such as nuclear industries, governmental institutions, hospitals and universities, among other sources.

Neutron activation analysis is the most simple and most widely used analytical application of RRs. In the case of commercialization of NAA, attention should be paid to the implementation of automation in all phases including sample irradiation, sample measurement, data acquisition, quality control and realization of a quality management system. Care should be taken not to exaggerate the analytical characteristics of NAA during commercial communication and to be well aware of the advantages and limitations of competing non-nuclear techniques.

Radioisotope production and NTD of Si remain the primary income generating commercial applications of RRs. While some startup costs may be absorbed by the operating organization, cost recovery for production, qualification and distribution should be the goal.

Neutron methods should not try to compete with well established non-destructive testing tools. Neutron methods have the disadvantage of immobility, high operational costs and availability only at a small number of neutron sources and via dedicated instruments. They can be used, however, to achieve reference data for validation of materials models and calibration of conventional non-destructive testing tools or performance of niche services, for which other techniques cannot compete. The results of neutron methods enhance the reliability of lifetime predictions, enabling less conservative quality control decisions without reducing the degree of safety. The appropriate use of neutrons in reference methods can be highly cost effective to commercial users.

Non-destructive testing with neutrons is commonly used to improve knowledge of material structures and quality control of various objects. The present applications of neutron beams are corrosion studies in metals; behaviour of moisture in building materials; and distribution of hydrogen, oil or lubricants in mechanical equipment such as fuel cells and car engines.

Scientific customers may also contribute significantly to the utilization, if not the revenue, of a RR. Accordingly, public relevance and reactor utilization are often more important than generating income only.

Nevertheless, there is an urgent need for quantitative information on the economic impact of RR services to end users. Such information may not always be easily retrievable in matters of customer confidentiality. Still, scientists should try to retrieve such information since it will contribute positively to the acceptance, preservation and possibly expansion of the reactor’s potential. It is expected that this document will at least partially mitigate these challenges and contribute to the enhancement of utilization and sustainability of RRs through the commercial products and services these facilities can provide.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Research Reactor Data Base (RRDB), available at http://nucleus.iaea.org/RRDB/, last accessed in December 2012.

[2] JEVREMOVIC, T., CHOE, D., SATVAT, N., XIAO, S., YANG, X., "In support of nuclear engineering manpower training — Experience from Utah program: R&D as integral part of curriculum; reactor training; experiential learning tools for international experience exchanges", Nuclear Engineering and Safety Workshop, Hanoi (2010).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Workforce Planning for New Nuclear Power Programmes, IAEA Nuclear Energy Series NG-T-3.10, IAEA, Vienna (2011).

[4] RIDIKAS, D., et al., "New opportunities for enhanced RR utilization through networks and coalitions", Proc. International Conf. on Research Reactors: Safe Utilization and Effective Management, Rabat, 2011, IAEA, Vienna (2012).

[5] HAWARI, A.I., MALKAWI, S., "Needs and present status of the first multipurpose nuclear facilities in Jordan", International Conf. on Research Reactors: Safe Utilization and Effective Management, Rabat, 2011, IAEA, Vienna (2012).

[6] NUCLEAR ENERGY AGENCY, The Supply of Medical Radioisotopes: An Economic Study of the Molybdenum-99 Supply Chain, NEA/OECD 6967, OECD, Paris (2010), https://www.nea.fr/ndd/reports/2010/nea6967-radioisotpes-full-report.pdf.

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, The Applications of Research Reactors, IAEA-TECDOC-1234, IAEA, Vienna, (2001).

[8] KRZYSZTOSZK, G., JAROSZEWICZ, J., PYTEL, K., "Irradiation of HEU targets in MARIA RR for Mo-99 production", Commercial Products and Services of Research Reactors, IAEA-TECDOC-1715, IAEA, Vienna (2013); see CD-ROM attached to this document.

[9] PARK, U.J., et al., "Production and development of radioisotopes in HANARO", Commercial Products and Services of Research Reactors, IAEA-TECDOC-1715, IAEA, Vienna (2013); see CD-ROM attached to this document.

[10] PONSARD, B., BLOWFIELD, H., "Production of radioisotopes and NTD-silicon in the BR2 reactor", Commercial Products and Services of Research Reactors, IAEA-TECDOC-1715, IAEA, Vienna (2013); see CD-ROM attached to this document.

[11] HATTINK, J., et al., "The production and use of ^{67}Cu as pharmacokinetic and toxicokinetic copper tracer via the ^{67}Zn (n,p) ^{67}Cu reaction", Proc. of the 5th International Conference on Isotopes, Brussels, 2005, Medimond, Bologna (2005).

[12] MUSHTAQ, A., et al., "Production Logistics and Prospects of ^{142}Pr and ^{143}Pr for Radionuclide Therapy (RNT) Applications", ibid.

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Neutron Transmutation Doping of Silicon at Research Reactors, IAEA-TECDOC-1681, IAEA, Vienna (2012).

[14] VON AMMON, W., "Neutron transmutation doped silicon — technological and economic aspects", Nuclear Instrumentation and Methods **B 63** (1992) 95.

[15] GERSTENBERG, H., "Industrial and commercial applications of FRM II", Commercial Products and Services of Research Reactors, IAEA-TECDOC-1715, IAEA, Vienna (2013); see CD-ROM attached to this document.

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Research Reactor Activities in Support of National Nuclear Programmes, IAEA-TECDOC-409, IAEA, Vienna (1987).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Practical Aspects of Operating a Neutron Activation Analysis Laboratory, IAEA-TECDOC-564, IAEA, Vienna (1990).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Use of Research Reactors for Neutron Activation Analysis, IAEA-TECDOC-1215, IAEA, Vienna (2001).

[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Aspects of Research Reactor Operations for Instrumental Neutron Activation Analysis, IAEA-TECDOC-1218, IAEA, Vienna (2001).

[20] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantifying Uncertainty in Nuclear Analytical Measurements, IAEA-TECDOC-1401, IAEA, Vienna (2004).

[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality System Implementation for Nuclear Analytical Techniques, IAEA Technical Course Series TCS 24, Vienna, 2004.

[22] INTERNATIONAL ATOMIC ENERGY AGENCY, Analytical Applications of Nuclear Techniques, IAEA STI/PUB 1181, IAEA, Vienna (2004).

[23] ROSSBACH, M., et al., "Quality system implementation in Member States of the IAEA", Accreditation and Quality Assurance **10** 11 (2006) 583–589.

[24] DE SOETE D. GIJBELS R., HOSTE J., Neutron Activation Analysis, John Wiley, New York (1972) 827 pp.

[25] GLADNEY E.S., MOSS, W.D., GAUTHIER, M.A., BELL, M.G., "Determination of U in urine: Comparison of ICP-MS spectrometry and delayed neutron assay", Health Physics **57** (1989) 171–175.

[26] BENZING, R., PARRY, S.J., BANGHINI, N.M., DAVIES, J.A., "Environmental and personnel monitoring for uranium by delayed neutron counting", The Science of the Total Environment (1991).

[27] FURUKAWA, Y., KOYAMA, M., YUKI, M., "Determination of boron content in several mediums by prompt gamma ray analysis", Radioisotopes **16** (1967) 7–11.

[28] GLADNEY, E.S., JURNEY, E.T., CURTIS, D.B., "Nondestructive determination of boron and cadmium in environmental materials by thermal neutron-prompt gamma-ray spectrometry," Analytical Chemistry **48** (1976) 2139–2142.

[29] CURTIS, D.B., GLADNEY, E.S., JURNEY, E.T., "A revision of the meteorite based cosmic abundance of boron", Geochimica et Cosmochimica Acta **44** (1980) 1945–1953.

[30] KOBAYASHI, T., KANDA, K., "Microanalysis system of PPM-order ^{10}B concentrations in tissue for neutron capture therapy by prompt gamma ray spectrometry", Nuclear Instruments and Methods **204** (1983) 525–531.

[31] FAILEY, M.P., ANDERSON, D.L., ZOLLER, W.H., GORDON, G.E., LINDSTROM, R.M., "Neutron-capture prompt gamma-ray activation analysis for multi-element determination in complex samples", Analytical Chemistry **51** (1979) 2209–2221.

[32] ISENHOUR, T.L., MORRISON, G.H., "Modulation technique for neutron capture gamma-ray measurements in activation analysis", Analytical Chemistry **38** (1966) 162–167.

[33] INTERNATIONAL ATOMIC ENERGY AGENCY, Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis, IAEA Technical Reports Series, IAEA, Vienna (2006).

[34] PAUL, R.L., LINDSTROM, R.M., "Prompt gamma-ray activation analysis: Fundamentals and applications", Journal of Radioanalytical and Nuclear Chemistry, **243** 1 (2000) 181–189.

[35] Handbook of Prompt Gamma Activation Analysis, MOLNAR, G.L, Ed., Kluwer Academic Press, Boston (2004) 423 pp.

[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Small Angle Neutron Scattering: Report of a Coordinated Research Project 2000–2003, IAEA-TECDOC-1486, IAEA, Vienna (2006).

[37] INTERNATIONAL ATOMIC ENERGY AGENCY, Neutron Imaging: A non-destructive tool for Materials Testing; Report of a Coordinated Research Project 2003–2006, IAEA-TECDOC-1604, IAEA, Vienna (2008).

[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Neutron Reflectometry: A probe for materials surfaces; Proceedings of a Technical Meeting, Vienna, 16–20 August 2004, IAEA STI/PUB/1246, IAEA, Vienna (2006).
[39] SCHNEIDER, R., "Industrial/commercial use of neutron diffraction for residual stress analysis", presented at IAEA Technical Meeting on Commercial Products and Services of Research Reactors, Vienna, 2010; see CD-ROM attached to this document.
[40] MONDAL, S.K., "Operation and utilization of Indian research reactor Dhruva", ibid.
[41] VAN DIJCK, S, et al., "Experimental irradiations of materials and fuels in the BR2 reactor: An overview of current programs", ibid.
[42] CHUE-INTA, S., et al., "Utilization of the Thai Research Reactor (TRR/M-1)", ibid.
[43] HAMPEL, G., EBERHARDT, K., "Utilization of the research reactor TRIGA Mainz", ibid.
[44] CENTRAL BRAIN TUMOR REGISTRY OF THE UNITED STATES, CBTRUS Statistical Report: Primary Brain and Central Nervous System Tumors Diagnosed in the United States in 2004–2008, March 23, 2012 rev., CBTRUS, Hinsdale (2012) 29 pp.
[45] INTERNATIONAL ATOMIC ENERGY AGENCY, Strategic Planning for Research Reactors, IAEA-TECDOC-1212 IAEA, Vienna (2001).
[46] BODE, P., HEYDORN, K., INNES, R.W., WOOD, R., ZEISLER, R., "Basic steps towards a self-sustainable quality system and laboratory accreditation", Accreditation and Quality Assurance **3** (1998) 197–202.

ABRREVIATIONS

AAS	Atomic absorption spectrometry
AECL	Atomic Energy of Canada Limited
ANSTO	Australia Nuclear Science and Technology Organisation
BNCT	Boron neutron capture therapy
CARR	China Advanced Research Reactor
CCD	Charge coupled device
DNC	Delayed neutron counting
EOI	End of irradiation
HEU	Highly enriched uranium
IAEA	International Atomic Energy Agency
ICP-MS	Inductively couple plasma mass spectrometry
INAA	Instrumental neutron activation analysis
IRE	National Institute for Radioelements (Belgium)
ISO	International Organization for Standardization
LEU	Low enriched uranium
MTR	Material Test Reactor
NAA	Neutron activation analysis
NPP	Nuclear power plant
NTD	Neutron transmutation doping
NTP	Nuclear Technology Products (Proprietary), Ltd. (South Africa)
OECD-GMP	Organisation for Economic Co-operation and Development Good Manufacturing Practise
OPAL	Open Pool Australian Lightwater reactor
PGNAA	Prompt gamma neutron activation analysis
QA/QC	Quality assurance/quality control
RNAA	Radiochemical neutron activation analysis
RR	Research reactor

RRDB	Research Reactor Database
SANS	Small angle neutron scattering
SPECT	Single photon emission computed tomography
SWOT	Strengths/weaknesses/opportunities/threats
TR-XRF	Total reflection X ray fluoresence
WANO	World Association of Nuclear Operators

LIST OF INDIVIDUAL PAPER CONTRIBUTIONS

All contributed presentations and papers are available in the attached CD-ROM.

TOPIC 1. TECHNICAL MEETING INTRODUCTION

Author	Affiliation	Paper
D. Ridikas	International Atomic Energy Agency, Austria	Commercial Products and Services of Research Reactors

TOPIC 2. UNIVERSITY AND TRAINING REACTORS

Author	Affiliation	Paper
P. Bode	Delft University of Technology, Netherlands	Contributions of Radiochemistry and Nuclear Analytical Techniques to Society and Technology: Some Examples of 35 Years' Experience in Delft
P. Bode	Delft University of Technology, Netherlands	Science and Service at a University Research Reactor
H. Böck	Atominstitut, Austria	Nuclear Education and Training Courses as a Commercial Product of a Low Power Research Reactor
H. Gerstenberg	Munich Technical University, Germany	Industrial and Commercial Applications of FRM II
G. Hampel	Johannes Gutenberg University Mainz, Germany	Utilisation of the Research Reactor TRIGA Mainz
T. Jevremovic	University of Utah, USA	Research Reactor Utilization at the University of Utah for Nuclear Education, Training and Services
S. Parry	Imperial College, UK	Commercial NAA — Is It a Success? Evaluation of a Twenty Year Experiment
B. Smodiš	Jožef Stefan Institute, Slovenia	Present Services at the TRIGA Mark II Reactor of the JSI
D. Wegrzynek	IAEA Laboratories, Austria	Air Quality Monitoring with Routine Utilization of Ion Beam Analysis

TOPIC 3. SMALL REACTOR UTILIZATION

Author	Affiliation	Paper
C. Chilian	Polytechnical School of Montréal, Canada	Possibilities of a Commercial Neutron Activation Analysis Service with a Small Reactor
S. Chue-inta	Thailand Institute of Nuclear Technology, Thailand	Utilization of the Thai Research Reactor (TRR-1/M1)
A. Jibre	National Center of Energy, Science and Nuclear Techniques (CNESTEN), Morocco	An Overview of Strategic Utilization Plan for the Moroccan Nuclear Research Reactor over the Period of 2010-2015
M.A.H. Khalid	Malaysian Nuclear Agency, Malaysia	Applications and Services at PUSPATI TRIGA Reactor In Malaysia — Current Status and Outlook
M. Korun	Jožef Stefan Institute, Slovenia	Self-Reliance and Sustainability of Nuclear Analytical Laboratories in Small States of Central Europe: The Slovenian Case
M. Mitev	Institute for Nuclear Research and Nuclear Energy, Bulgaria	Strategy for Sustainable Utilization of IRT-Sofia Research Reactor
N. Nhi Dien	Dalat Nuclear Research Institute, Vietnam	Effective Utilization of the Dalat Research Reactor for Radioisotope Production, Neutron Activation Analysis, Research and Training
N. Xoubi	Jordan Atomic Energy Commission, Jordan	Jordan Research and Training Reactor (JRTR) Utilization Facilities

TOPIC 4. LARGE REACTOR UTILIZATION

Author	Affiliation	Paper
D. Barbos	Institute for Nuclear Research, Romania	INR- TRIGA Research Reactors: a Neutron Source for Radioisotopes and Materials Investigation
Z. Chai	Institute of High Energy Physics, China	Nuclear Analytical Techniques for Commercial Applications in China
K. Mendis	Australian Nuclear Science and Technology Organisation, Australia	The Utilisation of Australia’s Research Reactor, OPAL
S.K. Mondal	Bhabha Atomic Research Centre, India	Operation and Utilization of Indian RR Dhruva
M. Salhi	Nuclear Research Center Birine, Algeria	Techniques and Nuclear Applications around Es Salam Reactor, Status and Future Potential
M.K. Shaat	Egyptian Atomic Energy Authority, Egypt	Products and Services of Research Reactor ETRR-2
F. Shen	China Institute of Atomic Energy, China	The Present Status and Future Potential Applications of RRs in CIAE

TOPIC 5. RADIOISOTOPES AND SILICON

Author	Affiliation	Paper
T. Hossain	AMD, Inc., USA	Applications of Nuclear Analytical Methods for High Tech Industry
G. Krzysztoszek	Institute of Atomic Energy POLATOM, Poland	Irradiations of HEU Targets in MARIA RR for Mo-99 Production
A. Mushtaq	Pakistan Institute of Nuclear Science and Technology, Pakistan	Production of Radioisotopes in Pakistan Research Reactor: Past, Present and Future
S.J. Park	Korea Atomic Energy Research Institute, Korea, Rep.	Neutron Transmutation Doping in HANARO Reactor
U.J. Park	Korea Atomic Energy Research Institute, Korea, Rep.	Production and Development of Radioisotopes in HANARO
B. Ponsard	Belgian Nuclear Research Centre (SCK·CEN), Belgium	Production of Radioisotopes and NTD-Silicon in the BR2 Reactor

TOPIC 6. MATERIAL STUDIES

Author	Affiliation	Paper
K.N. Choo	Korea Atomic Energy Research Institute, Korea, Rep.	The Contribution of HANARO to the R&D relevant to the SMART and VHTR System
M. Ishihara	Japan Atomic Energy Agency, Japan	Present Status and Future Potential for Commercial Application of JAEA Research Reactors
R. Schneider	VDI/VDE Innovation + Technik GmbH, Germany	Industrial/Commercial Use of Neutron Diffraction for Residual Stress Analysis
S. Van Dyck	Belgian Nuclear Research Centre (SCK·CEN), Belgium	Experimental Irradiations of Materials and Fuels in the BR2 Reactor
D. Wegrzynek	IAEA Laboratories, Austria	Commercial Applications of X Ray Spectrometric Techniques

IAEA
International Atomic Energy Agency

No. 22

Where to order IAEA publications

In the following countries IAEA publications may be purchased from the sources listed below, or from major local booksellers. Payment may be made in local currency or with UNESCO coupons.

AUSTRALIA
DA Information Services, 648 Whitehorse Road, MITCHAM 3132
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788
Email: service@dadirect.com.au • Web site: http://www.dadirect.com.au

BELGIUM
Jean de Lannoy, avenue du Roi 202, B-1190 Brussels
Telephone: +32 2 538 43 08 • Fax: +32 2 538 08 41
Email: jean.de.lannoy@infoboard.be • Web site: http://www.jean-de-lannoy.be

CANADA
Bernan Associates, 4501 Forbes Blvd, Suite 200, Lanham, MD 20706-4346, USA
Telephone: 1-800-865-3457 • Fax: 1-800-865-3450
Email: customercare@bernan.com • Web site: http://www.bernan.com

Renouf Publishing Company Ltd., 1-5369 Canotek Rd., Ottawa, Ontario, K1J 9J3
Telephone: +613 745 2665 • Fax: +613 745 7660
Email: order.dept@renoufbooks.com • Web site: http://www.renoufbooks.com

CHINA
IAEA Publications in Chinese: China Nuclear Energy Industry Corporation, Translation Section, P.O. Box 2103, Beijing

CZECH REPUBLIC
Suweco CZ, S.R.O., Klecakova 347, 180 21 Praha 9
Telephone: +420 26603 5364 • Fax: +420 28482 1646
Email: nakup@suweco.cz • Web site: http://www.suweco.cz

FINLAND
Akateeminen Kirjakauppa, PO BOX 128 (Keskuskatu 1), FIN-00101 Helsinki
Telephone: +358 9 121 41 • Fax: +358 9 121 4450
Email: akatilaus@akateeminen.com • Web site: http://www.akateeminen.com

FRANCE
Form-Edit, 5, rue Janssen, P.O. Box 25, F-75921 Paris Cedex 19
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90
Email: formedit@formedit.fr • Web site: http://www. formedit.fr

Lavoisier SAS, 145 rue de Provigny, 94236 Cachan Cedex
Telephone: + 33 1 47 40 67 02 • Fax +33 1 47 40 67 02
Email: romuald.verrier@lavoisier.fr • Web site: http://www.lavoisier.fr

GERMANY
UNO-Verlag, Vertriebs- und Verlags GmbH, Am Hofgarten 10, D-53113 Bonn
Telephone: + 49 228 94 90 20 • Fax: +49 228 94 90 20 or +49 228 94 90 222
Email: bestellung@uno-verlag.de • Web site: http://www.uno-verlag.de

HUNGARY
Librotrade Ltd., Book Import, P.O. Box 126, H-1656 Budapest
Telephone: +36 1 257 7777 • Fax: +36 1 257 7472 • Email: books@librotrade.hu

INDIA
Allied Publishers Group, 1st Floor, Dubash House, 15, J. N. Heredia Marg, Ballard Estate, Mumbai 400 001,
Telephone: +91 22 22617926/27 • Fax: +91 22 22617928
Email: alliedpl@vsnl.com • Web site: http://www.alliedpublishers.com

Bookwell, 2/72, Nirankari Colony, Delhi 110009
Telephone: +91 11 23268786, +91 11 23257264 • Fax: +91 11 23281315
Email: bookwell@vsnl.net

ITALY
Libreria Scientifica Dott. Lucio di Biasio “AEIOU”, Via Coronelli 6, I-20146 Milan
Telephone: +39 02 48 95 45 52 or 48 95 45 62 • Fax: +39 02 48 95 45 48
Email: info@libreriaaeiou.eu • Website: www.libreriaaeiou.eu

JAPAN
Maruzen Company Ltd, 1-9-18, Kaigan, Minato-ku, Tokyo, 105-0022
Telephone: +81 3 6367 6079 • Fax: +81 3 6367 6207
Email: journal@maruzen.co.jp • Web site: http://www.maruzen.co.jp

REPUBLIC OF KOREA
KINS Inc., Information Business Dept. Samho Bldg. 2nd Floor, 275-1 Yang Jae-dong SeoCho-G, Seoul 137-130
Telephone: +02 589 1740 • Fax: +02 589 1746 • Web site: http://www.kins.re.kr

NETHERLANDS
De Lindeboom Internationale Publicaties B.V., M.A. de Ruyterstraat 20A, NL-7482 BZ Haaksbergen
Telephone: +31 (0) 53 5740004 • Fax: +31 (0) 53 5729296
Email: books@delindeboom.com • Web site: http://www.delindeboom.com

Martinus Nijhoff International, Koraalrood 50, P.O. Box 1853, 2700 CZ Zoetermeer
Telephone: +31 793 684 400 • Fax: +31 793 615 698
Email: info@nijhoff.nl • Web site: http://www.nijhoff.nl

Swets and Zeitlinger b.v., P.O. Box 830, 2160 SZ Lisse
Telephone: +31 252 435 111 • Fax: +31 252 415 888
Email: infoho@swets.nl • Web site: http://www.swets.nl

NEW ZEALAND
DA Information Services, 648 Whitehorse Road, MITCHAM 3132, Australia
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788
Email: service@dadirect.com.au • Web site: http://www.dadirect.com.au

SLOVENIA
Cankarjeva Zalozba d.d., Kopitarjeva 2, SI-1512 Ljubljana
Telephone: +386 1 432 31 44 • Fax: +386 1 230 14 35
Email: import.books@cankarjeva-z.si • Web site: http://www.cankarjeva-z.si/uvoz

SPAIN
Díaz de Santos, S.A., c/ Juan Bravo, 3A, E-28006 Madrid
Telephone: +34 91 781 94 80 • Fax: +34 91 575 55 63
Email: compras@diazdesantos.es, carmela@diazdesantos.es, barcelona@diazdesantos.es, julio@diazdesantos.es
Web site: http://www.diazdesantos.es

UNITED KINGDOM
The Stationery Office Ltd, International Sales Agency, PO Box 29, Norwich, NR3 1 GN
Telephone (orders): +44 870 600 5552 • (enquiries): +44 207 873 8372 • Fax: +44 207 873 8203
Email (orders): book.orders@tso.co.uk • (enquiries): book.enquiries@tso.co.uk • Web site: http://www.tso.co.uk

On-line orders
DELTA Int. Book Wholesalers Ltd., 39 Alexandra Road, Addlestone, Surrey, KT15 2PQ
Email: info@profbooks.com • Web site: http://www.profbooks.com

Books on the Environment
Earthprint Ltd., P.O. Box 119, Stevenage SG1 4TP
Telephone: +44 1438748111 • Fax: +44 1438748844
Email: orders@earthprint.com • Web site: http://www.earthprint.com

UNITED NATIONS
Dept. I004, Room DC2-0853, First Avenue at 46th Street, New York, N.Y. 10017, USA
(UN) Telephone: +800 253-9646 or +212 963-8302 • Fax: +212 963-3489
Email: publications@un.org • Web site: http://www.un.org

UNITED STATES OF AMERICA
Bernan Associates, 4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4346
Telephone: 1-800-865-3457 • Fax: 1-800-865-3450
Email: customercare@bernan.com · Web site: http://www.bernan.com

Renouf Publishing Company Ltd., 812 Proctor Ave., Ogdensburg, NY, 13669
Telephone: +888 551 7470 (toll-free) • Fax: +888 568 8546 (toll-free)
Email: order.dept@renoufbooks.com • Web site: http://www.renoufbooks.com

Orders and requests for information may also be addressed directly to:

Marketing and Sales Unit, International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 (or 22530) • Fax: +43 1 2600 29302
Email: sales.publications@iaea.org • Web site: http://www.iaea.org/books

International Atomic Energy Agency
Vienna
ISBN 978–92–0–143610–8
ISSN 1011–4289