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European Nuclear Society
Rue Belliard 65
1040 Brussels, Belgium
Phone + 32 2 505 30 54
Fax +32 2 502 39 02
E-mail ens@euronuclear.org
Internet www.euronuclear.org

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Session III:

Utilisation of Research Reactors

EDUCATION AND TRAINING IN NUCLEAR ENERGY: STATE OF ART, NEEDS AND FUTURE STRATEGIES

HELMUTH BÖCK
Vienna University of Technology
Atominstitue
Stadionallee 2, A-1020, Vienna, Austria

ABSTRACT

During the past three decades the interest of students in nuclear energy decreased due to the fact that especially in Europe and the US no new nuclear power plants were ordered and many industrialised countries even voted for a nuclear phase out program such as Germany, Italy, or Sweden. This trend was immediately reflected in the university enrolment and students turned to other areas such informatics, robotics, nano-technology etc. Nuclear education and training possibilities were drastically reduced as research reactors were shut down and university curricula were reduced. Today as a nuclear renaissance is obvious, this lack of students in the nuclear field during the past two decades overlaps with the fact that many senior staff members reach their age of retirement both in research centres, nuclear power plants and academia.

Therefore the nuclear industry desperately needs qualified graduates in the nuclear field. To reverse this trend since several years many national and international organisations were established or added new programs to their existing structure to support these efforts such as the IAEA, OECD, ENEN-Association, the World Nuclear University, the German Kompetenzverbund, Asian ANENT, Belgium BNEN, British NTEC to name a few. In addition common academic curricula were established to facilitate mutual recognition and mobility of professors and students (Bologna Agreement). In parallel in many countries new university chairs in the nuclear field were filled with young professors. In addition a few new powerful research reactors were commissioned (FRM-2, OPAL) or are under construction (JHR) and planning (PALLAS). This paper describes the present international state of nuclear education, training and analyse the future needs of industry and research.

1. Background

About three decades ago, the development of nuclear power technology was hit by some severe local and global accidents. For example, the reactor fire at Browns Ferry, Alabama, in 1975 or the core meltdown at Three Mile Island in 1979. Then the Chernobyl disaster in 1986 initiated a further decline trend especially in industrialized countries. Most of the ordered nuclear plants were cancelled. Worldwide, about 34 reactors in 2007 are listed to be under construction mainly in Asia and Russia. Japan and France, with large nuclear programs, heavily subsidize their plants, France uses a single design and built their plants mainly to ensure some minimum strategic energy independence [1].

It is now difficult to repeat the investment and construction ratios as compared to 1980s because today the nuclear industry and utilities have more challenges than in the past. Today this sector needs to deal primarily with waste management and decommissioning expenses that far outweigh estimates of the past. In particular, it has to face the problems of rapid loss of competence and lack of manufacturing infrastructure. One of the biggest challenges is the supply of qualified people, including craft labour, technicians, engineers and scientists, to support both construction and operation of nuclear facilities.

Today, nuclear technology is widespread and multidisciplinary and it needs to be continued because of its vital role in our daily lives. It has been recognized globally that the advancement of this technology along with all its associated benefits has been threatened due to the declining number of university programs. The declination in the development of nuclear technology, unfortunately, mainly happened due to its safety concerns. This decreased the level of public acceptance up to critical limits which turned the situation into the lack of industry interests, governmental strategies for nuclear technology research and infrastructure. These factors have drastically declined the enrolments in university-based nuclear engineering programs which, in turn, have led to the closure of many of these programs [2].

2. Academic challenges

Most of the countries have now fewer comprehensive, high-quality nuclear technology programmes at universities than before. The universities ability to attract top-quality students to those programmes, meet future staffing requirements of the nuclear industry and conduct leading-edge research in nuclear topics has become seriously compromised. Followings are the main concern [3].

1. The decreasing number and the dilution of nuclear programmes at university levels.
2. The decreasing number of students taking nuclear subjects.
3. The lack of young faculty members to replace ageing and retiring faculty members.
4. Ageing research facilities, which are being closed and not replaced.
5. The significant fraction of nuclear graduates not entering the nuclear industry.

The importance of nuclear knowledge, its preservation and enhancement has been recognized globally [1]. To sustain all peaceful activities regarding utilization of nuclear technology, the qualified nuclear human resources are required. The most crucial element is the demand for graduates and highly qualified personals as these are essentials for; (1) operation of existing facilities (2) capacity building (3) innovation and R&D

These demands are usually satisfied by the higher educational institutions; the universities and associated institutes. The universities as well as other integrated institutions can not work in isolation. For nuclear higher education, the closely interacting partners with the universities are nuclear industries and related training institutes. The functioning of all these entities is guided by the need of the economic stability and growth thrust. Due to an economics driven operation the policy from the Governments plays an important role as well. From country to country the interaction of government's policies may vary to universities, industries and training institutes, but it has a major role to play in the demand of human resources and hence on the nuclear higher education trends.

3. Future Strategies

1. The severe imbalance between demand and supply, requires an efficient Human Resource Development (HRD) system to assure the continuity over time in the needed capacities, skills and knowledge. This HRD system is important to establish and maintain a pool of manpower variously trained in different nuclear-related skills and educated in nuclear relevant fields.
2. The education and training institutions are workforce supplier to industry and other R&D organizations. Their mutual cooperation may raise the performance level.
3. The governments are responsible for its strategic energy planning. They can support the public awareness of nuclear education, manpower and infrastructure. This would definitely increase the input to academia from public and input to industries from academia. The industries, by maintaining the quality of product, can attract the student careers effectively toward academia.
4. Funding is considered an important component to produce a sustainable workforce supply. Both government and industry have important role in funding support toward activities of nuclear knowledge management and its preservation. The access to national laboratories and industrial facilities for students is required to improve the situation.
5. The top quality curricula can produce good quality of nuclear workforce.
6. The effective implementation of nuclear safety knowledge is not only important for the safety of plant personnel and the general public but also in improving public perception which play fundamental role in sustainment of nuclear technology.

4. Networking

Networking is a useful tool to exchange experts, information and facilities. Networking of educational institutions has been recognized widely as a key strategy for capacity building and better use of available educational resources. In the field of NKM the networking has become an important element of nuclear education and training and shaping its character. By practice, its benefits have been acknowledged, and networks are being established on all levels i.e. national, regional and global levels. The networking might even become more important in the future, both in terms of numbers and cooperation intensity [4].

The following national and international networks are playing active role in promotion of nuclear technology by their various kinds of activities. The details of these networks (objectives, members, achievements and their national/international activities) can be seen under their given web links.

4.1 International Educational Networks

- Asian Network for Higher Education in Nuclear Technology (ANENT), http://www.anent-iaea.org/anent/index.jsp
- European Nuclear Education Network (ENEN), http://www.enen-assoc.org/
- World Nuclear University (WNU), www.world-nuclear-university.org/

4.2 National Educational Networks

- Belgium Nuclear higher Education Network (BNEN), Belgium, www.sckcen.be/bnen
- Consorzio Interuniversitario per la Ricerca Tecnologica Nucleare (CIRTEN), Italy, http://www.enen-assoc.org/en/about/enen-membership/effective-member/cirten.html
- Nuclear Technology Education Consortium (NTEC), UK, http://www.ntec.ac.uk/
- University Network of Excellence in Nuclear Engineering (UNENE), Canada, www.unene.ca/

5. Selected country surveys on the present situation and outlook

5.1 Canada

To establish a sustainable supply of qualified nuclear engineers and scientists to meet the current and future needs of the Canadian industry, the UNENE network was launched [6]. For this task, industry is invests significant funds in selected universities and contributes in-kind to enable the universities to acquire and retain the highest quality of teaching and research professoriate. The enrolments in and the number of qualified personnel from the full-time Masters, Doctoral and Post-Doctoral programs have exceeded the targets set for 2005 with the exception of a slight shortfall in the Masters program. The Phase 1 operation of UNENE planned output of High Qualified Personnel (HQP) is shown in Fig. 1.The decreasing nature of the both curves will indeed be compensated with the start of Phase 2.

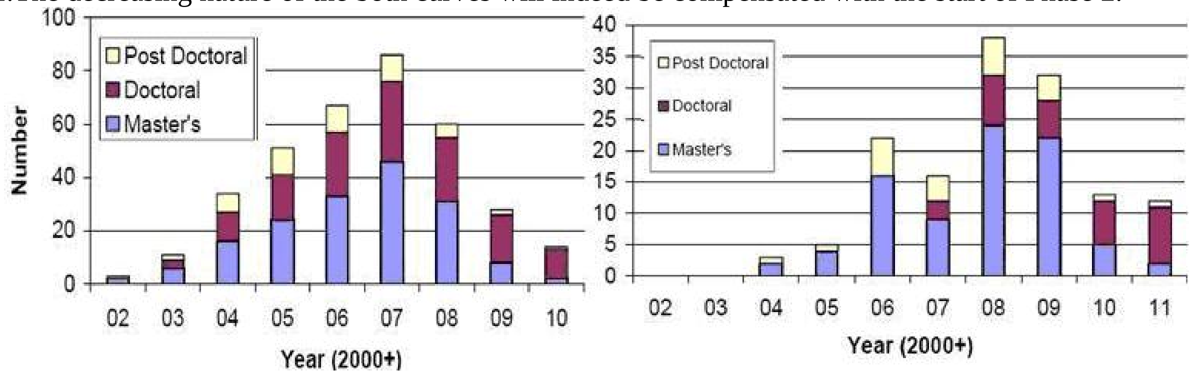

Fig 1: Enrolment of research student (left), HQP trained in the first phase of UNENE (right) [6]

5.2 France

France produces, almost half (45%) of the nuclear electricity in the EU27 and drives about 80% of its nuclear energy because of long standing policy based on energy security. More than 4200 engineers have been graduated since 1955 and this trend is shown in Fig. 2 [7, 8].

The nuclear workforce situation is not better in France. About 40% of the national utility EDF's current staff in reactor operation and maintenance will retire by 2015. Starting in 2008, the utility will try to hire 500 engineers annually. Reactor builder AREVA has already hired 1600 engineers in 2008 and 2009 in Germany alone. It is obvious that the biggest share of the hired staff are not trained nuclear engineers or other nuclear scientists. The CEA affiliated national Institute for Nuclear Sciences and Techniques (INSTN) has only generated about 50 nuclear graduates per year. EDF has called upon the institute to double the number over the coming years [1].

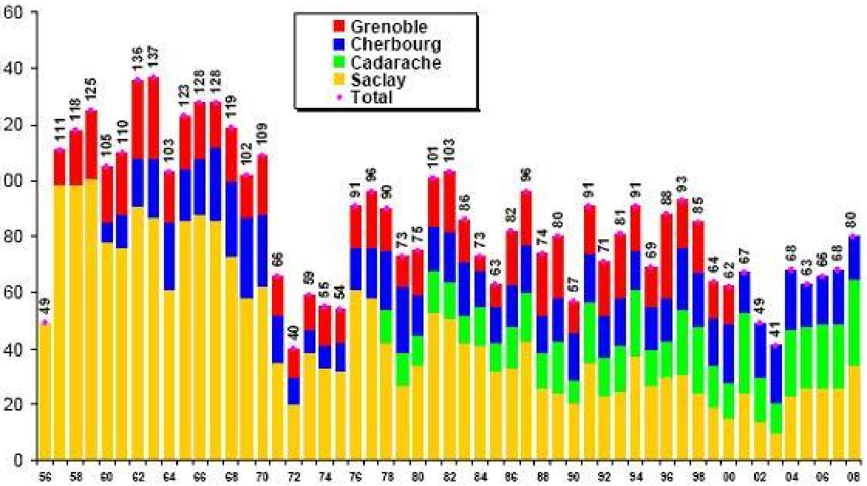

Fig 2: Trends of nuclear graduates (1955-2008) in France [8]

5.3 Germany

According to a 2004 analysis of the nuclear education and workforce development in the country, the situation continues to erode rapidly. employment is expected to decline in the nuclear sector - including the reactor building and maintenance industry - by about 10% to 6 250 jobs in 2010, these include still 1,670 hires. The number of academic institutions teaching nuclear related matters declined from 22 in 2000 to 10 in 2005 and only five in 2010, however a few new chairs in the nuclear field have been filled recently. While 46 students obtained their diploma in 1993, they were zero in 1998. In fact, between the end of 1997 and the end of 2002 only two students successfully finished their nuclear studies. In total about 50 students from other options continue to attend lectures in nuclear matters. It is clear that Germany will face a dramatic shortage of trained staff, both in industry, utilities, research or public safety and radiation protection authorities [9].

5.4 UK

The decline in UK public fission and R&D funding is provided in Fig.3 which reflects the status history of nuclear education in UK. The following skills survey and reports were performed on this issue [10].

- HSE/NII education & research in UK universities (2002)
- DTI nuclear skills group (2002)
- Nuclear Task Force (Ruffles, 2003)
- COGENT Nuclear employers survey (200)
- NDA Health Physics Resources in UK Industry (Rankine, 2007)

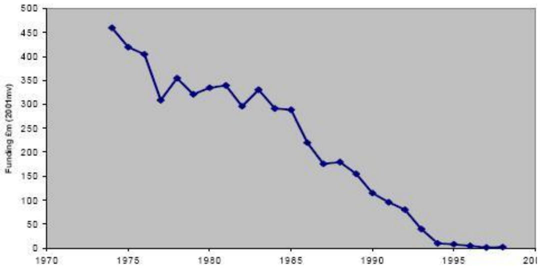

Fig 3: Decline in UK public fission funding [10]

The BNFL Energy Unit advised to the government and research councils to keep the nuclear option open. Therefore strategic needs are now recognised and new funds have been made available for nuclear education & research [5]. The UK has just launched a nuclear industry oriented National Skills Academy that is intended to improve the standard of industry training, increase productivity and tackle skills shortages across the UK. The nuclear training activities in the UK are coordinated by the NTEC directed by the University of Manchester.

5.5 USA

Between 1962 to 1980 the USA was enjoying a peak in nuclear technology with 64 university research reactors, 50 nuclear engineering programs and 1800 plus students,. The incidents like TMI and Chernobyl as well as rising financial cost resulted into loss of public support, cancellation of orders, decline in nuclear engineering enrolment and shutdown of research reactors as shown in Fig.4 [2]. Serious considerations by DOE were addressed to these decline problems. Further the NERAC ad hoc panel considered seriously the educational situation related to the future of nuclear science and engineering [2]. Such efforts revive several programs, as reflected by Fig.5 [1].

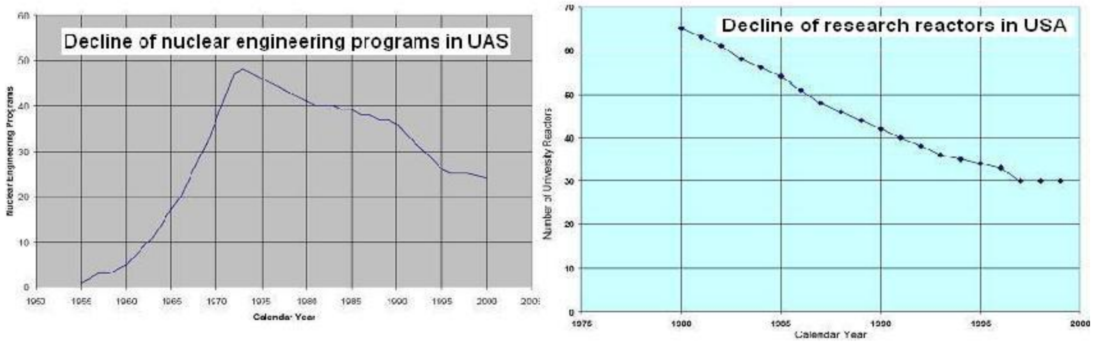

Fig 4: Nuclear engineering enrolments (left) and decline of research reactor (right) [2]

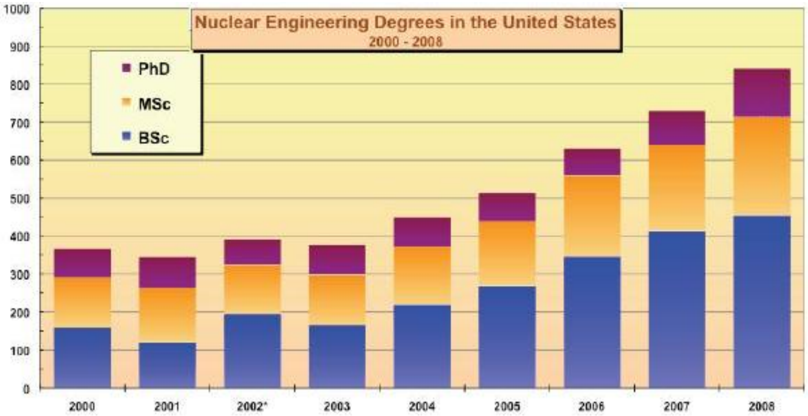

Fig 5. Trends of nuclear engineering graduates in USA 2000-2008 [1]

Acknowledgement

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UTILIZATION OF SLOVENIAN TRIGA MARK II REACTOR

L. SNOJ, B. SMODIŠ
Reactor Infrastructure Centre, Jožef Stefan Institute
Jamova cesta 39, SI-1000 Ljubljana, Slovenia

ABSTRACT

TRIGA Mark II research reactor at the Jožef Stefan Institute [JSI] is extensively used for various applications, such as: irradiation of various samples, training and education, verification and validation of nuclear data and computer codes, testing and development of experimental equipment used for core physics tests at a nuclear power plant. The paper briefly describes the aforementioned activities and shows that even such small reactors are still indispensable in nuclear science and technology.

1. Introduction

TRIGA Mark II research reactor at the Jožef Stefan Institute (JSI) is extensively used for various applications, such as: irradiation of various samples, training and education, verification and validation of nuclear data and computer codes, testing and development of experimental equipment used for core physics tests at the Krško Nuclear Power Plant. In the paper, all of the above mentioned activities are presented and briefly described together with the references for further information.

The purpose of the paper is to present the utilization of the TRIGA Mark II reactor at JSI and show that even small reactors such as 250 kW TRIGA at JSI can still be used for various purposes and can significantly contribute to state of the art achievements in the field of nuclear science and technology and other related fields.

2. Irradiation of samples

The TRIGA research reactor JSI is used for irradiation of various samples. It has been mainly used for neutron activation analysis [1] and for irradiation of various components for the ATLAS detector in CERN [2,3]. Due to relatively large “triangular” channel it enables the irradiation of silicon detectors at different temperatures by installing a heating/cooling module inside the channel. Due to good characterization of the irradiation channels the JSI TRIGA Mark II reactor is a reference centre for neutron irradiation of detectors developed for the ATLAS experiment.

The reactor is used for irradiation of silicon detectors and related radiation damage studies:

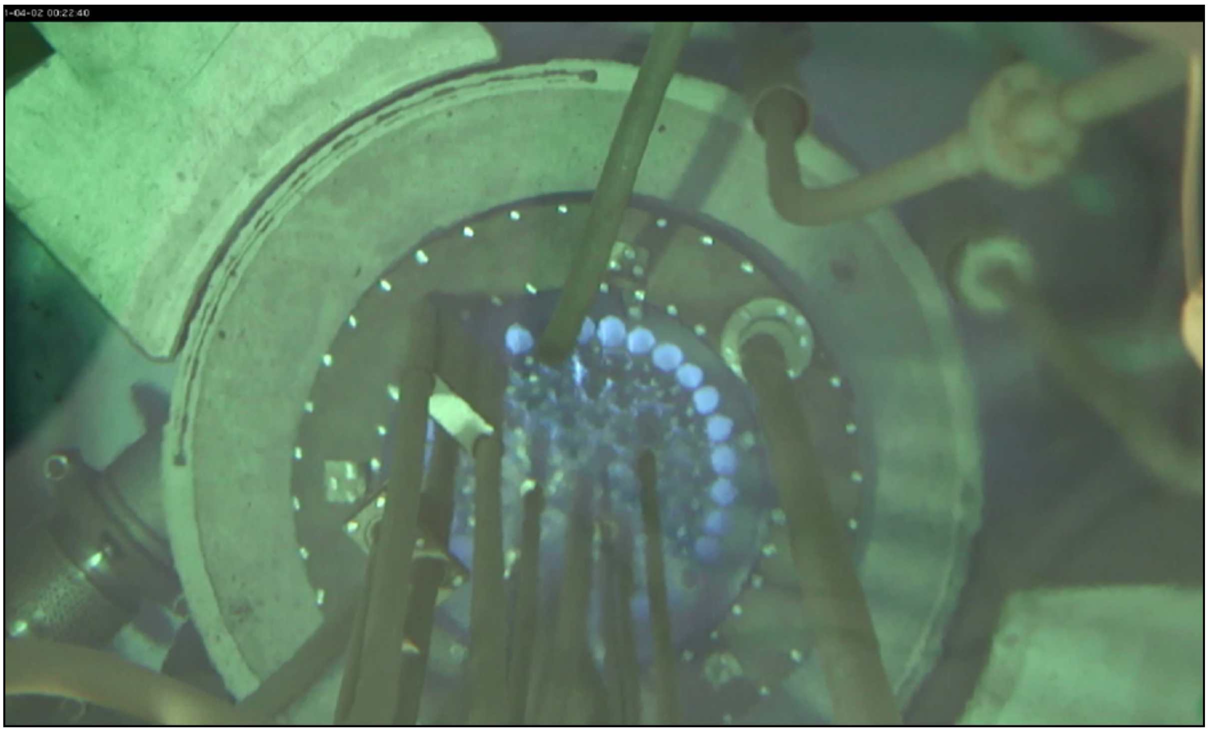
- Irradiation of samples of detector material
- Irradiation of reading electronics

In addition to that two projects have been initiated recently; the development and improvement of future fusion reactor materials and the development of bio-dosimeters. They both demand a large number of irradiations under different conditions (neutron spectra and flux) and subsequent gamma spectral analyses of the samples. Both activities together with results are thoroughly presented and described in conference papers [4, 5, 6]

3. Training and Education

Practically all nuclear professionals in Slovenia started their career or attended practical training courses at the TRIGA reactor (including all professors of nuclear engineering and reactor physics at Ljubljana and Maribor Universities, as well as directors and key personnel of the Nuclear Power Plant (NPP) Krško, the Slovenian Nuclear Safety Administration and the Agency for Radioactive Waste]. All NPP Krško reactor operators and other technical staff pass training courses on the TRIGA reactor; the reactor is used in regular laboratory exercises for graduate and post graduate students of physics and nuclear engineering at the Faculty of Mathematics and Physics, Ljubljana University. The reactor has been used in several international training courses, the latest one being organised by the Eastern Europe Research Reactor Initiative [EERRI] [7].

Since 2009 the JSI TRIGA reactor has been equipped with teleconference system, and two full high definition (HD) (1080 × 1920 pixel) digital cameras which represent the basis for installation of remote training capabilities. The two full HD cameras are installed above the core but can be submersed also under water in a specially designed leak tight casing. Both cameras feature also 10 × optical zoom, which allow the users to visually inspect the core or individual fuel elements. Both cameras can be operated from the control room and the picture is also displayed there on a 132 cm big full HD screen. This new features are extremely useful especially for observing the core at practical exercises such as critical experiment, where fuel elements are moved around and the source is withdrawn and at void coefficient exercise, in which voids are inserted in different positions in the core and reactivity is measured. Our experience show that the new system enhances the understanding of the experiments ad makes all practical exercises more attractive.



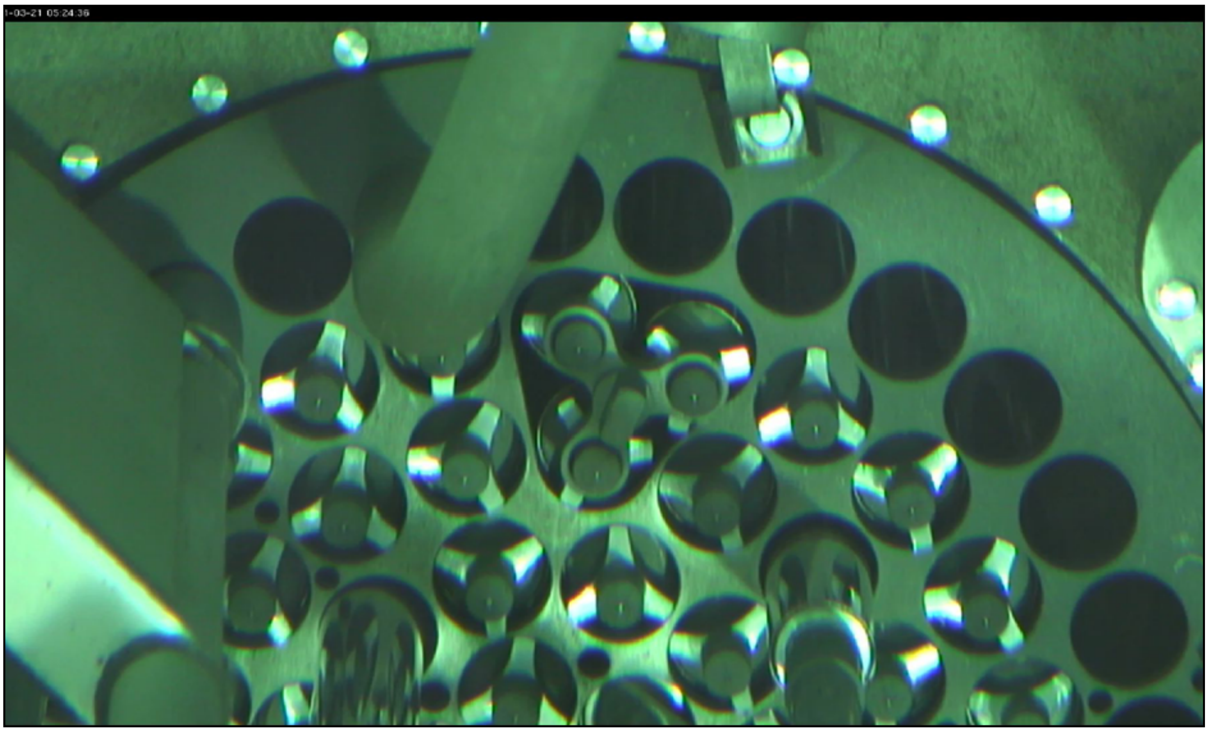


Figure 1: A view of the JSI TRIGA Mark II core with the new cameras. Wide angle [top] and 10 × close-up [bottom]

4. Verification and validation of computer codes and nuclear data

The user of any computer code should not only know how the code works but has to be familiar also with the validity and the limitations of the code. Therefore one has to verify the code and the computational model by performing a comparison of the calculated results with benchmark experiments also called benchmarks. Moreover one has to validate also the input data, usually the cross section data, used in the calculations.

Several well defined and carefully designed experiments have been performed at the TRIGA Mark II research reactor at JSI, in order to establish a set of benchmarks for TRIGA reactors. All of them have been thoroughly analyzed and the experimental uncertainties evaluated by using the most advanced Monte Carlo neutron transport codes such as MCNP [8]. Criticality experiments performed in 1991 have been thoroughly evaluated and are included in the ICSBEP handbook [9, 10]. They present the reference case for criticality calculations with UZrH fuel. Recent measurements of neutron spectra and neutron flux distribution are candidates for becoming benchmark experiments for neutron spectra and neutron flux calculations in UZrH fuelled systems [11-13]. A series of pulse experiments are candidates for TRIGA kinetic parameters benchmark [14-16]. In the following sections the main findings are briefly presented.

4.1 Criticality calculations

In order to verify and validate the calculations of multiplication factor in TRIGA reactor, the TRIGA criticality benchmark from the International Handbook of Evaluated Criticality Safety Benchmark Experiments was used [9]. The benchmark experiments were performed as part of the start-up test after reconstruction and upgrading in 1991. All core components (top and bottom grid plates, fuel, control rods, irradiation channels), with the exception of the graphite reflector around the core were replaced with new ones in the process. The experiments in steady-state operation were performed with completely fresh fuel (including instrumented elements containing thermocouples and fuelled followers of control rods) in a compact and uniform core (all elements including the fuelled followers of control rods were of the same type with no non-fuel components in the critical core configuration) at well controlled operating conditions. The benchmark experiment was performed with standard commercial TRIGA fuel elements of 20 % enrichment and 12 wt. % uranium concentration in U-ZrH1.6.

Two realistic benchmark core configurations were examined [9], denoted as core 132 and core 133. The benchmark k_{eff} values together with the measurement uncertainties and the calculated values (calculated with MCNP version 5.1.40) of k_{eff} are presented in Table 1.

Table 1: Benchmark model k_{eff} and calculated values of the benchmark k_{eff} using different cross-section libraries.

Cross section set → Case ↓	**Benchmark-model k_{eff}**	**ENDF/B-VI.8**	**ENDF/B-VII**	**JEFF 3.1**
Core 132	1.0006 ± 0.0056	1.0001 ± 0.0001	1.0059 ± 0.0001	1.0019 ± 0.0001
Core 133	1.0046 ± 0.0056	1.0048 ± 0.0001	1.0107 ± 0.0001	1.0063 ± 0.0001

To conclude, we have observed that we can well reproduce the benchmark k_{eff} with MCNP code, indicating that our computational model describes the reactor geometry and material properties sufficiently well for performing criticality calculations. However the calculated values of k_{eff} strongly depend on the cross section library used in calculations. In future emphasis should be put on improvement of nuclear data libraries.

4.2 Neutron flux distribution

The second step in the process of computational model validation is the validation of spatial neutron flux distribution. The process involves activation experiments to validate the calculated results. The measured activities are compared to the calculated ones to validate the calculated spatial distribution of the fast and thermal plus epithermal neutron flux, making sure that no important geometrical features of the structural components are omitted from the model.

The verification of neutron flux distribution was performed by comparing the calculated and measured $^{27}Al(n,\alpha)^{24}Na$ and $^{197}Au(n,\gamma)^{198}Au$ reaction rates in irradiation channels in the core centre, at the core periphery and in the graphite reflector surrounding the core. The results are thoroughly discussed and presented in several papers and reports [11-13]. We observed that our computational model very well describes the neutron flux and reaction rate distribution in the reactor core. At the core periphery however, the accuracy of the epithermal and thermal neutron flux distribution and attenuation is decreased, mainly due to lack of information about the material properties of the graphite reflector surrounding the core.

Since our computational model properly describes the reactor core it can be used for calculations of reactor core parameters such as power distribution, power peaking factors [17], effective delayed neutron fraction and prompt neutron lifetime [18]. Moreover now that we have developed a very good computational model of the JSI TRIGA Mark II research reactor we can use it to support various activities such as validation of self-shielding factors [19, 20]

5. Testing and development of digital reactivity meter

The JSI TRIGA Mark II reactor is used also for testing and development of a digital reactivity meter and associated computational methods which are then used for performing core physics tests at the Krško NPP. All experimental equipment and computer codes were developed and tested at the JSI TRIGA Mark II reactor. Every year before the start-up test we test all equipments, go through all procedures, measure reactor core parameters (excess reactivity, control rod worth, reactor response to step reactivity insertion, etc) and prepare ourselves for the real start-up tests at the Krško NPP, which have to be completed in less than 14 hours. Hence a thorough preparation to the test is essential and could not be made without our TRIGA research reactor.

6. Conclusions

This paper briefly presents the major activities that are going on at the JSI TRIGA Mark II research reactor. It can be seen that although the reactor is over 40 years old, it still significantly contributes to new scientific achievements in nuclear science and to preservation of knowledge on nuclear energy.

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EXTENSIVE UTILISATION OF VR-1 REACTOR FOR NUCLEAR EDUCATION AND TRAINING

J. RATAJ
Department of Nuclear Reactors, Czech Technical University in Prague
V Holešovičkách 2, 180 00 Prague 8, Czech Republic

ABSTRACT

The paper presents utilisation of the VR-1 reactor for nuclear education and training at national and international level.

VR-1 reactor has been operating by the Czech Technical University since December 1990. The reactor is a pool-type light water reactor based on enriched uranium (19.7% ^{235}U) with maximum thermal power 1kW and for short time period up to 5kW. The moderator of neutrons is light water, which is also used as a reflector, a biological shielding and a coolant. Heat is removed from the core by natural convection. The pool disposition of the reactor facilitates access to the core, setting and removing of various experimental samples and detectors, easy and safe handling of fuel assemblies. The reactor core can contain from 17 to 21 fuel assemblies IRT-4M, depending on the geometric arrangement and kind of experiments to be performed in the reactor. The reactor is equipped with several experimental devices; e.g. horizontal, radial and tangential channels used to take out a neutron beam, reactivity oscillator for dynamics study and bubble boiling simulator.

The reactor has been used very efficiently especially for education and training of university students and NPP's specialists for more than 18 years. The VR-1 reactor is utilised within various national and international activities such as Czech Nuclear Education Network (CENEN), European Nuclear Education Network and also Eastern European Research Reactor Initiative (EERRI). The reactor is well equipped for education and training not only by the experimental facility itself but also by incessant development of training methods and improvement of education experiments. The education experiments can be combined into training courses attended by students according to their study specialization and knowledge level. The training programme is aimed to the reactor and neutron physics, dosimetry, nuclear safety, and control of nuclear installations. Every year, approximately 250 university students undergo training at VR-1 reactor. Their stay at reactor site means an enormous benefit for their study process.

1. Introduction

The training reactor VR-1, so-called "SPARROW", was commissioned in 1990 at the Department of Nuclear Reactors of the Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague. The reactor is used in education of technical university students, in R&D, in the education and training of specialists in the nuclear industry, and finally in promotional activities within the field of nuclear power.

The education and training is oriented to the reactor and neutron physics, dosimetry, nuclear safety, and control of nuclear installations. R&D has to respect reactor parameters and requirements of the so-called clean reactor core (free from major effects of the fission products). Research at the reactor is mainly aimed at the preparation and testing of new educational methodologies, investigation of reactor lattice parameters, reactor dynamics studies, research in the field of control equipment, neutron detector calibration, etc.

The VR-1 reactor is utilised within various national and international activities. The utilisation of VR-1 reactor at national level takes place within Czech Nuclear Education Network (CENEN). The international co-operation is based mainly on activities realised within

European Nuclear Education Network (ENEN) and Eastern European Research Reactor Initiative (EERRI).

2. Basic Technical Parameters of VR-1 Reactor

The VR-1 Training Reactor (see Fig1) is a pool-type light-water reactor based on enriched uranium with maximum thermal power 1kW and for short time period up to 5kW. The moderator of neutrons is light demineralised water, which is also used as a reflector, a biological shielding, and a coolant. Heat is removed from the core by natural convection. The pool disposition of the reactor facilitates access to the core, setting and removing of various experimental samples and detectors, easy and safe handling of fuel assemblies.

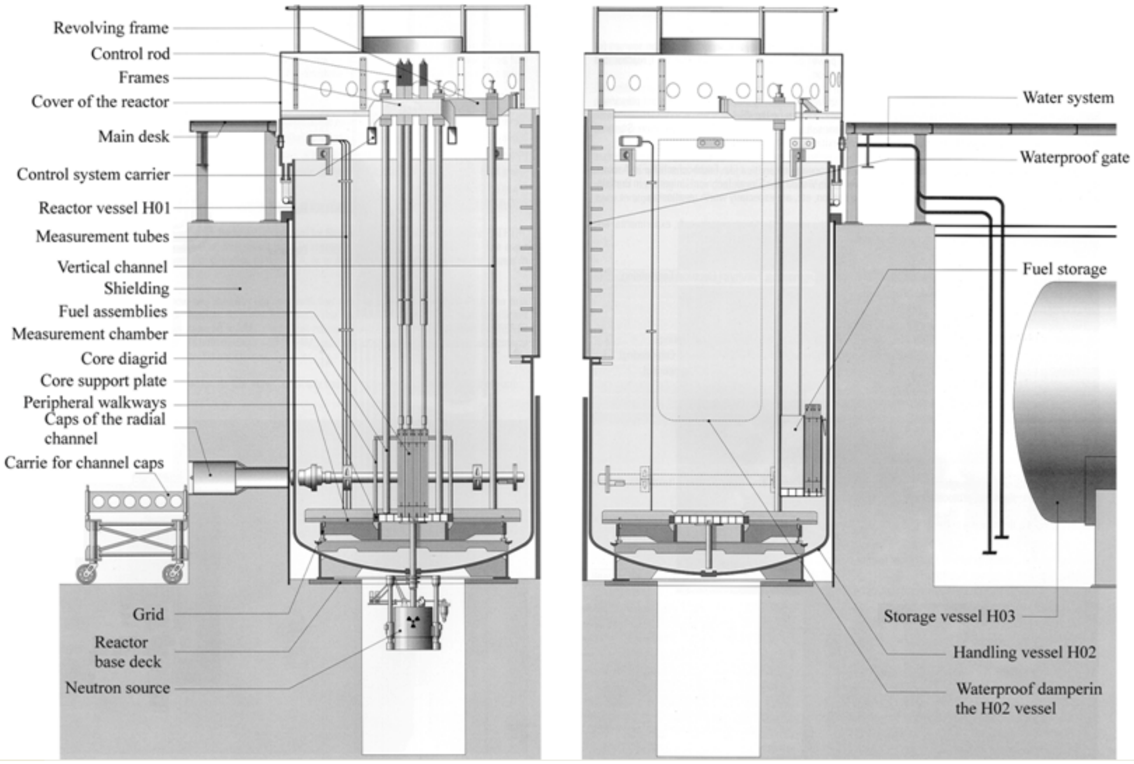

Fig 1. Cross section of VR-1 reactor

Reactor has been successfully converted from the highly enriched uranium (IRT-3M, enrichment: 36 % ^{235}U) fuel to the low enriched uranium (IRT-4M, enrichment: 19.7 % ^{235}U) fuel in 2005 [1]. The reactor core contains 17 to 21 fuel assemblies IRT-4M, depending on the geometric arrangement and kind of experiments to be performed in the reactor. The core is accommodated in a cylindrical stainless steel vessel - pool, which is filled with water.

The cadmium control rods serve the reactor control and safe shutdown. Construction of all the rods is identical, but they differ in their functions (safety, compensation or control) according to the connection with the control and safety system.

Digital control equipment consists from control and safety system, signalling system, connecting system, and neutron source control. The Am-Be neutron source is used to start up the reactor. It ensures a sufficient level of the signal at the output of the power measuring channels from the deepest sub-criticalities, and thus guarantees a reliable check of the power during the reactor start-up.

The reactor is equipped with several experimental devices [3]; e.g. horizontal, radial and tangential channels used to take out a neutron beam reactivity oscillator for dynamics study and bubble boiling simulator. Basic technical properties of the VR-1 reactor are summarised in Table 1.

Rated Power	1 kW (thermal), 5 kW for short time period

Neutron Flux	2 - 3×10^9 /cm^2.s
Fuel	IRT-4M type, ^{235}U enrichment 19,75 % (imported from Russia)
Reactor Vessels (pools)	made from stainless steel vessel diameter 2 300 mm vessel height 4 720 mm wall thickness 15 mm
Reactor Shielding	above core: water layer 3 000 mm side: water layer about 850 mm + concrete 950 mm
Temperature	20 °C (according to the ambient temperature)
Core Cooling	natural convection
Pressure	atmospheric
Control Rods	5-7 control rods: 3 safety (shut-down) rods, 0-2 experimental rods (according to the core configuration), 2 control rods
Operating Power Measurement	four wide-range non-compensated fission chambers
Independent power Protection	four pulse corona boron counters
Neutron Source	Am-Be, 185 GBq, emission rate of 1.1 . 10^7 s^{-1}

Tab 1. Basic technical properties of the VR-1 reactor

3. Education and Training at VR-1 Reactor

The training reactor VR-1 is principally used for training of students from technological universities and specialist from Nuclear Power Plants. Training is aimed to areas such as reactor physics, neutronics, dosimetry, reactor operation, nuclear safety and I&C systems.

Depending on the curriculum and orientation of individual users, the training is performed in the regular weekly schedule or in the form of batch courses two to five days long. The specific content of the courses is compiled according to the requirements of the users. The courses and experiments are available in three levels:

- demonstration;
- basic;
- advanced.

The demonstration level is intended for basic understanding of physical phenomenon, which is applied during the experiment and participants are rather passive observers. In the basic level, participants actively take part in the experiment, and independently evaluate acquired data. The advanced level is designed for in-depth study of the issue and requires a deeper theoretical knowledge of participants and their active participation in the preparation of measurements, during the experiment and interpretation of acquired values. A chosen phenomenon or process is often analysed using several different approaches or conditions.

Currently, over 25 experiments are prepared at the reactor [3]. The most frequent experiments are the following:

- basics of neutron detection using gas detectors;
- determination of gas detectors dead time;
- analysis of neutron detectors properties for reactor I&C;
- measurement of delayed neutrons;
- determination of neutron flux density distribution by tiny gas detectors,
- determination of neutron flux density distribution by activation detectors (Au foils, Cu wires);
- reactivity measurements (e. g., Rod Drop, Source Jerk, Positive Period);
- control rods calibration (e. g., by Inverse Count Rate);
- analysis of various materials impacts on reactivity;

- criticality approach and critical experiment;
- study of nuclear reactor dynamics;
- start-up, controlling and operation of nuclear reactor;
- bubble boiling simulation and its impact on reactivity;
- short-time instrumental neutron activation analysis.

The less frequent, specialized experiments aimed at determination of kinetic characteristics (e.g. neutron lifetime, effective delayed neutron fraction), selected analytical methods for the environment protection or extended experimental courses of digital control systems.

4. Utilisation of VR-1 Reactor within National and International Cooperation

VR-1 reactor as a specialized training facility of the Ministry of Education, Youth and Sports, is in addition to students of Czech Technical University in Prague open to students from other universities in the Czech Republic (more than five Czech universities). Majority of reactor training for students from the Czech universities takes place within the scope of CENEN (see Fig 2). Every year 150-200 students from Czech universities undergo training at VR-1 reactor. Student's stay at reactor site means an enormous benefit for their study process.

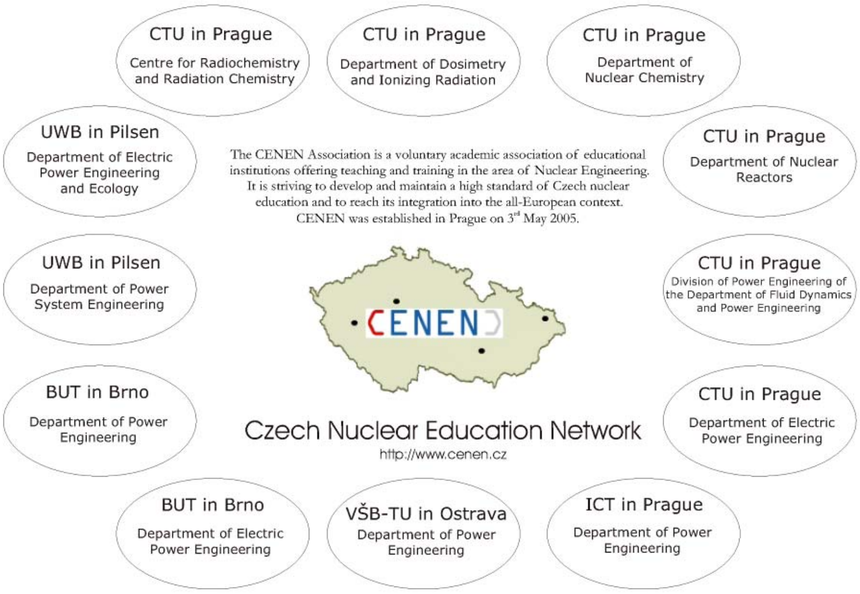

Fig 2. Scheme Diagram of Cooperation within CENEN Framework

The reactor is frequently used for training of NPP's specialists as well. The users are both from Czech NPPs (Dukovany and Temelín) and Slovak NPPs (Jaslovské Bohunice and Mochovce). Approximately 5 courses for NPP's staff take place at VR-1 reactor per year.

Integral part of reactor utilisation is education and training of students coming from abroad. There is close cooperation with Germany (Fachhochschulle Aachen), Slovakia (Slovak University of Technology in Bratislava), Sweden (KTH Royal Institute of Technology in Stockholm) and Austria (Atominstitut TU Vienna). Education for foreign students is also organized within the scope of ENEN. Approximately 40 foreign students take part in course at VR-1 reactor per year.

Several courses organised at VR-1 reactor in cooperation with IAEA. Currently there are activities related to EERRI. EERRI was established in 2008 and covers 8 research reactors (see Fig 3) from 6 European countries as an example of regional co-operation between research reactors. Soon after its establishment, the EERRI in collaboration with IAEA organised and successfully carried out the first group education and training course dedicated for the Members States aiming to build their first research reactor. The second course is already scheduled for April this year. The course will take place at VR-1 reactor as well.

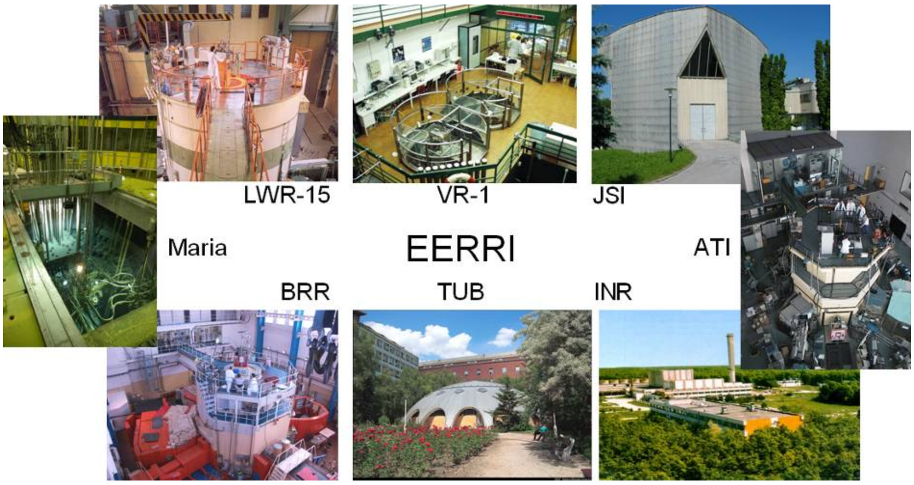

Fig 3 Research reactors utilised within EERRI
(LWR-15 and VR-1– Czech Republic, JSI – Slovenia, ATI – Austria,
INR – Romania, BRR and TUB – HUNGARY, Maria – Poland,)

Another important part of the VR-1 reactor utilisation is providing the public information. High-school or university students as well as public visit the reactor. Programme of visit is didactic; containing a lecture, a site visit, performance of a reactor operation and visitors also gather all important aspects of nuclear energy production. More than 1000 visitors come to VR-1 reactor per year.

5. Conclusions

The VR-1 reactor has been used very efficiently for nuclear education and training of university students and NPP’s specialists for more than 18 years. The utilisation of VR-1 reactor at national level takes place within CENEN. The international co-operation is based mainly on activities realised within ENEN, IAEA and EERRI. The operator and main user of the VR-1 reactor is the Czech Technical University in Prague; another five Czech universities participate in its use. The co-operation with foreign universities is frequent as well. Every year, approximately 250 university students undergo training at VR-1 Reactor. Further training courses are provided for specialists from Czech and Slovak NPPs. There are five special courses per year. Every year more than 1000 visitors come to VR-1 reactor within informational and promotional activities.

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SELF-SUSTAINABILITY OF A RESEARCH REACTOR FACILITY WITH NEUTRON ACTIVATION ANALYSIS

C. CHILIAN, G. KENNEDY

Department of Engineering Physics, Ecole Polytechnique
P.O. Box 6079, Montreal, H3C 3A7, Canada

ABSTRACT

Long-term self-sustainability of a small reactor facility is possible because there is a large demand for non-destructive chemical analysis of bulk materials that can only be achieved with neutron activation analysis (NAA). The Ecole Polytechnique Montreal SLOWPOKE Reactor Facility has achieved self-sustainability for over twenty years, benefiting from the extreme reliability, ease of use and stable neutron flux of the SLOWPOKE reactor. The industrial clientele developed slowly over the years, mainly because of research users of the facility. A reliable NAA service with flexibility, high accuracy and fast turn-around time was achieved by developing an efficient NAA system, using a combination of the relative and k0 standardisation methods. The techniques were optimized to meet the specific needs of the client, such as low detection limit or high accuracy at high concentration. New marketing strategies are presented, which aim at a more rapid expansion.

1. Introduction

1.1 Development of the reactor facility

Seven SLOWPOKE reactor facilities were constructed in Canada in the 1970’s and 1980’s. Four of them continue operating; three have been shut down and in each case a major factor leading to the decision to close the facility was that their attempts to attain self-sustainability were unsuccessful.

The Montreal facility began operation in 1976. The original mandate of the facility was to provide teaching in nuclear engineering and to provide neutron activation analysis to researchers at the university and in the Montreal region. The use of the reactor for teaching in nuclear engineering is still continuing at the Nuclear Engineering Institute.

The neutron activation analysis work began slowly because the original staff included no NAA expert. The staff learned from visits to other well-established facilities and soon began developing NAA techniques suited to this SLOWPOKE reactor and tailored to meet the needs of the university researchers. Funding was ensured by infrastructure grants from the Canadian government and from the government of the province of Quebec and from teaching and research funds available at Ecole Polytechnique. During the period 1976-1985, a large number of graduate students in science and engineering used the facility for NAA and then left to work in various industries or research centres. These former students, with the positive experience gained at the facility, were very important to the subsequent achievement of self-sustainability.

2. Achieving self-sustainability

2.1 Motivation

In 1985, the administration of Ecole Polytechnique announced that the university no longer had funds to support research and the reactor facility would have to become self-sustainable or would be shut down. The staff of the facility, who by then had five to eight years experience, felt that self-sustainability was possible and decided to make the long-term commitment to achieve it. Fortunately, the maintenance costs of a SLOWPOKE reactor were very low; thus more than 80% of expenses were salaries.

At this time, the revenues of the facility were NAA revenues and government infrastructure grants. It was necessary to increase the NAA revenues. Fig. 1 shows the evolution of the NAA revenues over the last 30 years. From 1985 to 1990 the revenues increased slowly because no special promotional effort was made to attract new clients. The increase was due completely to former research users, students and other researchers, who decided to begin using NAA again or who communicated the advantages of NAA to their colleagues. The large increases in 1991 and 1992 were due to these same users who started several large projects.

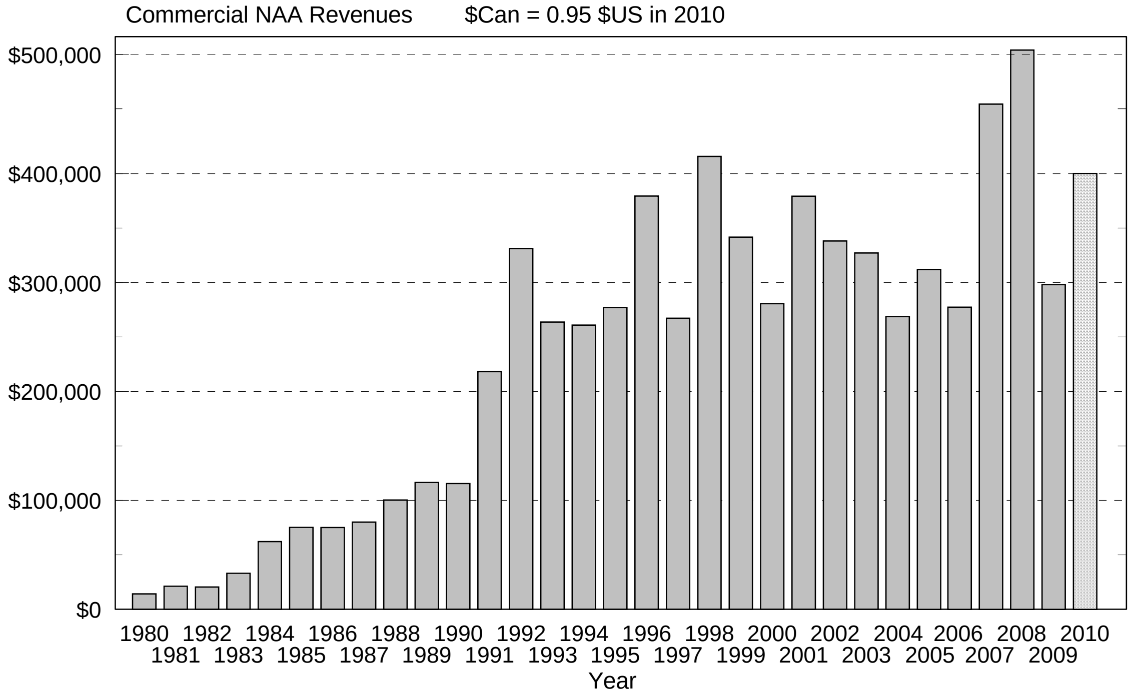

Fig 1. Commercial NAA revenues of the facility

2.2 Development of neutron activation analysis as a commercial product

Scientists at many facilities have the attitude that they understand very well neutron activation analysis, as it was developed in the 1970s and 1980s, and with their reactor and gamma-ray spectrometer they can apply this method successfully for a commercial NAA service. They offer fixed analysis packages, based on what is convenient for them, such as short half-life nuclides or long half-life nuclides or the availability of their reactor and staff. This attitude rarely leads to success; the NAA service must be developed to meet the needs of the customer.

We discuss at length with all potential customers to determine their exact needs and how we can best meet them. The method is adjusted for each new case, carefully taking into account the development cost. Most of our clients are industries that require NAA for product development and quality control. They require the following, with the most important items listed first:

- Fast turn-around time
- Reliability

- High accuracy
- High sensitivity
- Range of concentrations from low to high

The SLOWPOKE reactor is ideal for fast turn-around times because it is always available five days a week. New projects require some time for method development; after that the method is ready and the analysis can begin as soon as the samples are received. The limitation is usually the half-lives of the elements of interest and the interferences.

Reliability and accuracy depend on the expertise and vigilance of the NAA analyst. He must be aware of all possible interferences and the various matrix effects, including sample inhomogeneity, neutron self-shielding, gamma-ray absorption, spectrometer dead-time, etc. He must constantly strive to avoid mistakes such as in labelling samples, weighing and recording the measurement parameters. He should be aware of the importance to do so. Mistakes have been reduced by the use of written procedures, and all analyses are fully documented and verified. We have a non-formal quality assurance program based on a “culture of quality” and common sense. We feel this approach is superior to that of a formal quality assurance program with unmotivated staff.

The relatively low neutron flux of the SLOWPOKE reactor, ten times lower than larger research reactors, has not been found to be a limitation to the sensitivity that can be achieved. The detection limit depends mainly on the ability to resolve the peak of the gamma-ray of interest from the Compton background. We have developed optimised counting techniques and powerful spectrum analysis software [1] for this.

It is important to be able to analyse any material for any element, out of the 60 elements commonly measured by NAA, quickly and accurately. With the classical Relative Method, every time a sample is analyzed, a standard must be prepared for every element. This is very time consuming. Our Improved Relative Method [1] takes advantage of the extreme stability of the SLOWPOKE reactor and the gamma-ray spectrometers. We standardise for each element and each counting geometry once, store the sensitivity constants in libraries, and use them for years without modification. With each batch of samples analyzed, we irradiate no standards and no flux monitors, only quality control standards occasionally.

Differences in sample size and composition between the standards and the unknowns are corrected for, using accurate models of the activation and detection processes [2]. Now, with the k_0 standardisation method [3], it is not necessary to irradiate a standard of every element. The parameters of the models used with the k_0 method are now sufficiently accurate [4,5] that the concentrations of all elements can be determined in any material, using any irradiation channel and any detector configuration, without a standard of each element. We now use the k_0 method extensively. It required a great deal of effort to develop this method and perfect it, but once implemented it now offers large savings in time as well as improved flexibility and accuracy.

A major limitation to NAA was the inability to predict the amount of neutron self-shielding, especially for epithermal neutrons, in materials containing high concentrations of neutron absorbing elements. This severely limited the materials which could be analysed. We have recently developed a simple and accurate method for correcting neutron self-shielding [6], which has opened many new avenues for our commercial NAA service.

The NAA method has thus been developed to analyse the widest variety of materials; those most commonly analysed are shown in Table 1. In principle, about 65 elements can be determined by NAA; in practise, up to 40 elements can be detected in common materials. The complete sample scan that offered therefore includes these 40 elements.

Material	Elements
Plastics	all, especially Mg, Ti, Al, Cl, Sn, P
Treated wood	I, Sn, Cu, Cr, As, Br
Rocks, minerals	Au, U, Th, rare-earths
Air particulates on filters	heavy metals
Silicon semiconductors	all
Food supplements	Ca, Mg, Fe, Zn, Se
Materials for fuel cells, batteries	Pt, Ru, Cd
Coated paper	I, Cu
Oil refinery catalysts	Cl
Textiles	Ag, Cd, Ni, Sb, Cl, Br, I, S, P
Leather	Cr
Archaeological ceramics	all
Pharmaceutical products	various elements

Table 1: Materials analysed by NAA

2.3 Staff

Experience has shown that a self-sustainable NAA facility using a SLOWPOKE reactor needs, as a minimum, these four essential staff members:

1. Director of the facility, who is also the reactor manager.
2. NAA analyst. He is also a reactor operator.
3. NAA assistant. He would ideally also be a reactor operator.
4. Technician. An employee of the university, he works part-time maintaining the reactor systems and the gamma-ray spectrometers.

The director of the facility must have a business mentality, and he must also be an NAA expert, working with the NAA analyst and ready to replace him when necessary. As reactor manager, he must be a SLOWPOKE reactor operator and knowledgeable in reactor safety and regulatory matters. The director of the facility and the NAA analyst should be specialised experts, they should be highly motivated and should occupy long-term positions. The NAA assistant becomes more essential as the volume of work increases, but this person is highly desirable at all times because he may be needed to ensure a continuously available NAA service during the vacation period, etc. Other part-time staff include Radiation Safety Officer, Quality Assurance Officer, NAA salesman.

3. Maintaining self-sustainability

3.1 Difficulties

Although the reactor is ageing, maintenance costs have not increased substantially, apart from the successful fuel change [7] in 1997. However, provisions should be made to prevent prolonged reactor shutdown (one month is enough to lose major clients) due to ageing. In addition, replacing ageing personnel should be planned carefully. We have developed an ageing management program for the facility, including ageing equipment, documentation and personnel. When fully implemented, it should reduce the probability of prolonged shutdowns.

The increase in revenues from 1985 to 1999, see Fig. 1, correlated well with the increase in staff and salaries. However, from 2000 to 2009 the fairly constant revenues have not kept pace with the large increase in regulatory costs. The effort required to achieve and maintain conformity with international safety standards and with the Canadian Nuclear Safety Act, enacted in 2000, now requires the equivalent of one full-time staff member. Also, since 2003, some of the revenues must be put aside to constitute a decommissioning fund. Thus, an effort is now needed to increase revenues.

3.2 Recent efforts to increase revenues

After a complete analysis of the facility from a business perspective, it was concluded that the key elements for achieving self-sustainability are always the same: excellent NAA services (fast, accurate analysis) and constant communication with the customers: learning about their needs but also allowing the customer to learn more about the capabilities of the NAA laboratory. We estimate that there is still a large untapped market for NAA in Canada and the USA, estimated at $20,000,000 annually, which we can exploit with our unique expertise in this field. We now need to valorise our strengths mentioned above, by entering into contact with new customers.

On three occasions in previous years, advertising material, including NAA information sheets and price lists, had been sent by mail or by email to potential clients. This met with absolutely no success. In 2009 this was again attempted, this time trying to better target the key people in organisations likely needing NAA. Again there was no success.

The senior staff of the facility now attends trade meetings of the industries which traditionally require NAA. As a result, the knowledge of the needs of these industries was improved and the contacts made are expected to eventually lead to some new clients.

An agreement was reached with an experienced salesman of technical and analytical services. The previous contacts of this salesman are now being informed of the possibilities of NAA. This met with some success and has already led to new NAA contracts in several areas.

4. Conclusion

It has been shown how a neutron activation analysis laboratory can achieve and maintain self-sustainability, through careful long-term business-like planning, the development of technical expertise, and its application by highly motivated staff.

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Medical and Radiobiological Applications at the Research Reactor TRIGA Mainz

GABRIELE HAMPEL[1], CATRIN GRUNEWALD[1], JENS-VOLKER KRATZ[1], TOBIAS SCHMITZ[1], CHRISTIAN SCHÜTZ[1], STEPHAN WERNER[1], KLAAS APPELMAN[2], RAYMOND MOSS[2], MATTHIAS BLAICKNER[3], THOMAS NAWROTH[4], GERD OTTO[5] and HEINZ SCHMIDBERGER[6],

[1]Institute for Nuclear Chemistry, University of Mainz, Fritz-Strassmann-Weg 2, D-55099 Mainz, Germany
[2]Institute for Energy, Joint Research Centre, The Netherlands
[3]Molecular Medicine, Health & Environment Department, AIT Austrian Institute of Technology GmbH
[4]Department of Pharmacy and Toxicology, University of Mainz, Staudingerweg 5, D-55099 Mainz, Germany
[5]Department of Hepatobiliary, Pancreatic and Transplantation Surgery, University of Mainz, Langenbeckstr. 1, D-55131 Mainz, Germany
[6]Department of Radiooncology, University of Mainz, Langenbeckstr. 1, D-55131 Mainz, Germany

ABSTRACT

At the University of Mainz, Germany, a boron neutron capture therapy (BNCT) project has been started with the aim to expand and advance the research on the basis of the TAOrMINA protocol for the BNCT treatment of liver metastases of colorectal cancer. Irradiations take place at the TRIGA Mark II reactor. Biological and clinical research and surgery take place at the University and its hospital of Mainz. Both are situated in close vicinity to each other, which is an ideal situation for BNCT treatment, as similarly performed in Pavia, in 2001 and 2003.

The application of BNCT to auto-transplanted organs requires development in the methodology, as well as regard to the irradiation facility and is part of the complex, interdisciplinary treatment process. The additional high surgical risk of auto-transplantation is only justified when a therapeutic benefit can be achieved. A BNCT protocol including explantation and conservation of the organ, neutron irradiation and re-implantation is logistically a very challenging task.

Within the last years, research on all scientific, clinical and logistical aspects for the therapy has been performed. This includes work on computational modelling for the irradiation facility, tissue and blood analysis, radiation biology, dosimetry and surgery. Most recently, a clinical study on boron uptake in both healthy and tumour tissue of the liver and issues regarding dosimetry has been started, as well as a series of cell-biology experiments to obtain concrete results on the relative biological effectiveness (RBE) of ionizing radiation in liver tissue.

1. Introduction

The basic idea for BNCT dates back to the discovery of the neutron by Chadwick in 1932 [1]. Maurice Goldhaber was the first scientist to observe the $^{10}B(n,\alpha)^{7}Li$ reaction by irradiation of ^{10}B with thermal neutrons, which is the basis of BNCT [2]. Soon after this, the idea was born to apply this reaction in the medical field, especially for cancer treatment [3]. The reaction yields a ^{7}Li and an α-particle which are able to destroy tissue within a very short range (< 10 µm). This radiation is particularly effective against cancer if the ^{10}B is present in tumour cells in high concentrations, with at the same time, only small quantities of ^{10}B in healthy tissue. ^{10}B is very suitable due to its low toxicity, good biochemical synthetic compatibility and a high neutron cross section (3837 barn) for the therapy. The ^{10}B is distributed and delivered into the targeted cells by carrier molecules. The patient is then irradiated in a suitable facility with a neutron beam. The result is the complete destruction of the tumour tissue, while the healthy tissue is not seriously damaged [4]. Since the 1950s, there have been clinical studies on various kinds of cancer, e.g. glioblastoma multiforme, malignant melanoma, head and neck cancer [5]. BNCT for patients with multiple colorectal liver metastases was established at the University of Pavia with two cases being treated by Pinelli et al in 2001 and 2003 [6]. The ^{10}B carrier p-borono-phenylalanine (BPA) was used at an infusion rate of 300 mg/kg, the liver was explanted, perfused with preservation solution, irradiated in the thermal column of the TRIGA Pavia research reactor with thermal neutrons and then reimplanted (auto-transplantation). Both cases were deemed successful and gave rise to the assumption that BNCT could be a beneficial option for a large number of patients suffering from primary and secondary cancer of the liver. Therefore, at Mainz, the BNCT project is focused on the treatment of liver tumours. Irradiations take place at the thermal column of the TRIGA Mark II reactor [7] (see Figure 1) and surgery is carried out at the University Hospital of Mainz. Both facilities are situated in close vicinity to each other, which is an ideal situation for BNCT treatment. The thermal column is filled at six positions with special graphite blocks serving as removable stringers. These channels are used for the autoradiography and irradiation of cells, parts of the liver or later for the irradiation of the whole organ.

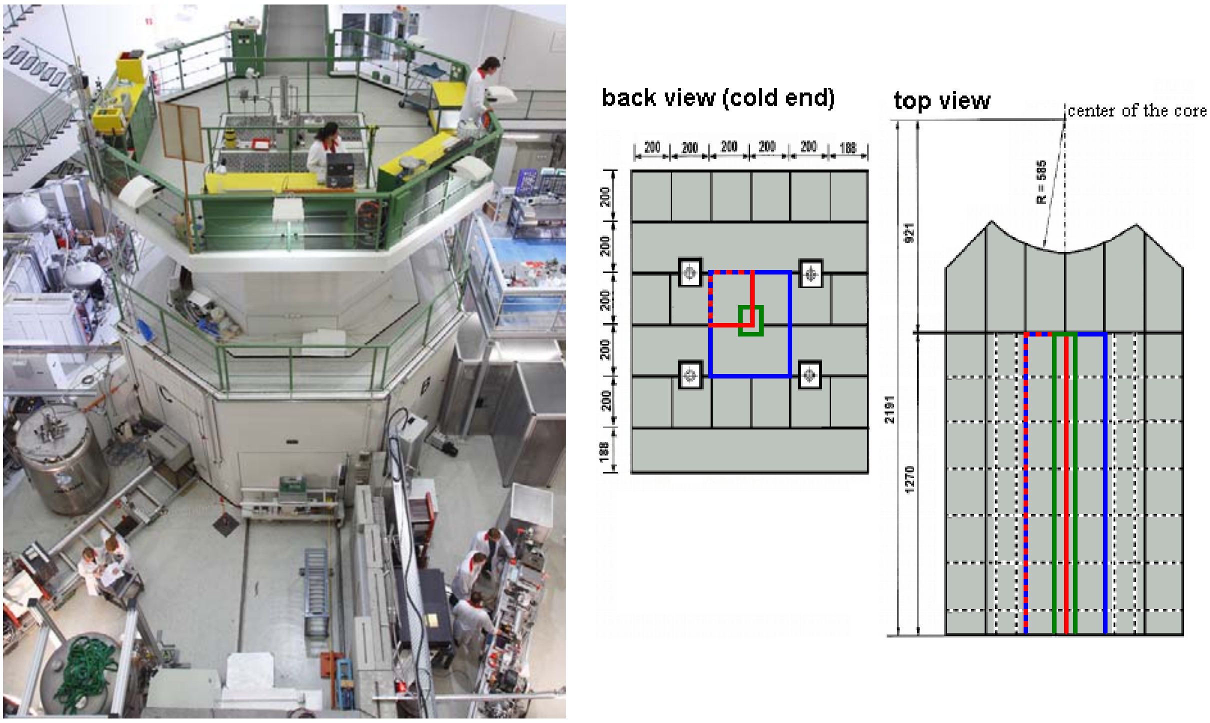

Figure 1: Left: The BNCT facility at the TRIGA Mainz, right: different irradiation positions of the thermal column: Channel for the radiography (green), for the irradiation of cells and the liver sections of the study (red), for the irradiation of the whole liver (blue)

2. Material and methods

2.1 Surgical procedure

Patients suffering from colorectal carcinoma develop distant metastases in 50 to 80 % of cases with the metastases being confined to the liver in almost half of these cases [8].

The surgical process requires extensive experience in the field of liver transplantation and preservation of the liver during the extracorporeal treatment. This includes perfusion of the liver artery with preservation solution and reducing the liver temperature to 4°C. The question remains whether there are any wash-out effects during this procedure and if yes, will the accumulation remaining in tumour tissue still be of sufficient concentrations for the irradiation therapy?

Therefore, the first step will be to determine the accumulation of BPA in tumour and healthy liver tissue in patients before and after partial liver resection and washing the liver specimen with preservation solution. Furthermore, additional pharmacokinetic data will be obtained from blood and urine samples taken at intervals during surgery.

At present, a clinical study with up to 15 patients is carried out to determine the boron uptake in both healthy and tumour tissue of the liver. The patients suffer from colorectal liver metastases and they need a partial liver resection. BPA was administered at a concentration of 200 mg/kg intravenously. Throughout the surgical procedure, blood samples were taken every 30 minutes (see figure 2).

Figure 2: Left: Perfusion of the partial liver after surgery; right: Taking samples of tumour and healthy tissue of the partial liver

2.2 Analytical methods

So far, samples have been provided from three patients. After the resection of the liver, the specimens were perfused with preservation solution (250 ml through the artery and 1500 ml through the portal vein) and tissue samples were taken from the surface and at depth in the organ to provide data for the spatial boron distribution. The samples were frozen in liquid nitrogen and prepared for analysis by the Department of Pathology, and for further analyses using autoradiography [9], and prompt gamma activation analysis (PGAA) [10].

Neutron autoradiography is applied for tissue analysis: CR-39 films overlaid with tissue slices containing ^{10}B were irradiated in the middle channel of the thermal column of the TRIGA Mainz together with a boron standard [9]. For development, the films were placed in 7M NaOH solution and then analysed using a microscope combined with a computed analysis.

PGAA was applied for the analysis of blood and healthy tissue sample at the High Flux Reactor in Petten, the Netherlands [11]. The method allows a direct determination of the ^{10}B concentration by the reaction $^{10}\mathrm{B} + \mathrm{n} \Rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He} + \gamma$. The samples were irradiated with thermal neutrons at the HB7 beam port [10]. The measurements of the emitted 478 keV gamma rays using a high purity germanium detector yield the ^{10}B content.

First results of the PGAA show a good correlation between the surgical procedure and the boron concentration in the blood (see figure 3). The analysis of the healthy and tumour tissue samples requires better statistics. Therefore, it is important to continue the study with the next patients.

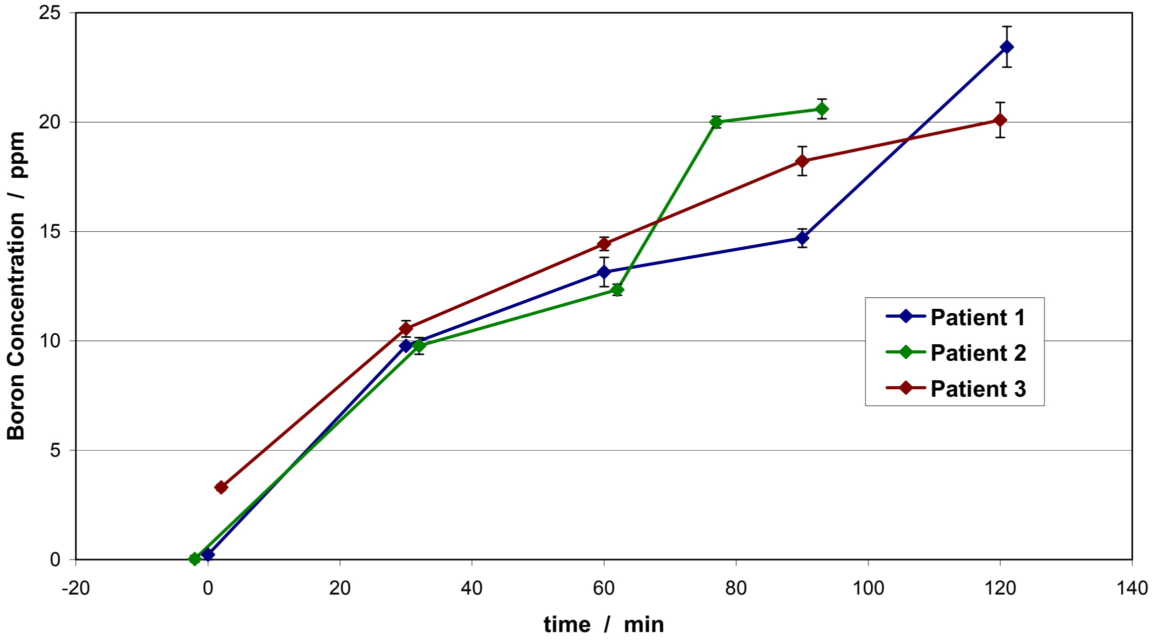

Figure 3: Pharmacokinetic curves for the first three patients of the study

2.3 Biological dosimetry

In order to determine the RBE for hepatocytes originating from healthy and tumour tissue, cell experiments were carried out. Cell lines of type Huh7 [12] which stem from two distinct persons containing differently modified tumour tissue were, treated with BPA and then irradiated with neutrons in the thermal column and with photons of a ^{60}Co gamma ray emitter.

At various times after irradiation, vitality of cells was measured using a cell proliferation assay. Growing curves of the irradiated cells were determined which allows to differentiate between apoptotic and necrotic effects in cells. The results of the different types of irradiation were compared to calculate factors for the RBE, which are important parameters in the evaluation later of radiotherapy.

2.4 Dose calculations for the irradiation facility

Simulations were carried out to model the irradiation field at the thermal column of the TRIGA Mainz for the purpose of preliminary dose calculations which serve as a first rough estimate for the efficiency of a future BNCT treatment [13]. The calculations of the irradiation field were validated using Au-activation foils and thermoluminescence dosimeter (TLD) [14].

Previously validated simulations using the Monte Carlo Code MCNP 5 [15] were applied to determine the spatial distribution of the neutron flux and the primary, as well as secondary, gamma dose in liver tissue at the planned irradiation site within the thermal column. The respective dose contributions for BNCT were calculated using the kerma approximation.

The results show that an effective BNCT treatment for extracorporeal livers irradiated in the modified thermal column of the TRIGA reactor in Mainz, even in the case of a low ratio of boron concentration in tumour (C_T) and normal liver tissue (C_N) respectively, is feasible. In the case that the C_T/C_N values are as reported in Pavia, the simulations yield a sufficient short irradiation time of 13 minutes, a maximum dose to normal tissue of 8 Gy and a minimum dose to tumour tissue of 32 Gy.

3. Conclusion

The thermal column of a TRIGA reactor is particularly suited for organ treatment, cell experiments, as well as the further development of neutron capture therapy. It will however be necessary to install additional Bi shielding inside the thermal column to reduce the gamma background. Different methods like autoradiography and PGAA are available to determine the boron concentration in blood and tissue samples. The clinical study to determine the boron uptake in healthy and tumour tissue of the liver has to continue to obtain better statistics of the boron concentration. Cell experiments have been started to determine the RBE and to develop a tumour model. Also simulations of the irradiation field in the thermal column and first dose calculations for the liver are being carried out to estimate the dose values for tumour and healthy tissue.

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IMPROVEMENT OF RESEARCH REACTOR SUSTAINABILITY

M. CIOCANESCU, C. PAUNOIU, C. TOMA, M.PREDA, M.IONILA
Institute for Nuclear Research Pitesti
No. 1, Campului Str., PO.Box-78, 115400-Mioveni, Romania

ABSTRACT

The Research Reactors as is well known have numerous applications in a wide range of science technology, nuclear power development, medicine, to enumerate only the most important. The requirements of clients and stack-holders are fluctuating for the reasons out of control of Research Reactor Operating Organization, which may ensure with priority the safety of facility and nuclear installation. Sustainability of Research Reactor encompasses several aspects which finally are concentrated on safety of Research Reactor and economical aspects concerning operational expenses and income from external resources. Ensuring sustainability is a continuous, permanent activity and also it request a strategic approach. The TRIGA – 14 MW Research Reactor detains a 30 years experience of safe utilization with good performance indicators. In the last 4 years the reactor benefited of a large investment project for modernization, thus ensuring the previous performances and opening new perspectives for power increase and for new applications. The previous core conversion from LEU to HEU fuel accomplished in 2006 ensures the utilization of reactor based on new qualified European supplier of TRIGA LEU fuel. Due to reduction of number of performed research reactors, the 14 MW TRIGA modernized reactor will play a significant role for the following two decades.

1. Introduction

Sustainable development is a general notion developed some two decades ago by Brundtland Report. Since that time the term was used, diversified and applied to a multitude of human activities, for example sustainable economy, sustainable agriculture, sustainable energy, sustainable nuclear energy. The content and sense of sustainability in fact is “oxymoron” and relative belonging to social economic environment to a plurality of cultures and technologies and contain a contradiction. The contradiction appears between natural resources regeneration and consumption of natural resources accomplished by the use of materials and dumping of waste. Sustainable means to keep equilibrium between resources consumption and regeneration with the condition to protect the environment. Sustainability in any area in general terms suppose:

- A long term vision – desired state = equilibrium
- A strategic approach – Planning
- Management of strategy – setting goals
- Sustainability measurement to measure progress
- Performance indicators
- Reporting and communication of achievements
- Feed back

A relative new approach of sustainability tries to explain the complex source of sustainability by thermodynamics fundamentals:

Principle 1 – The energy is not created or destroyed, the energy through technology is “only modified in form”

Principle 2 – Matter and energy trends to disperse in time to low level in environment, increasing the entropy.

Sustainability of Research Reactors could be understood as a human complex activity part of many other life processes developed in other areas as fundamental research, materials research, applicative research for nuclear energy, nuclear safety, agriculture, medicine, education and more others. Sustainability of Research Reactors is in a strong correlation with sustainability in other fields of activity challenged by principles of thermodynamics:

Principle 1 – Resources available for research reactors are modified in form through diverse technologies/techniques of neutrons generation utilization to become resources for other processes

Principle 2 – Resources trends to disperse in time to low level in environment, increasing the entropy i.e. reducing the sustainability.

Sustainability of Research Reactors is a part of sustainable development of science, technology, energy and the demand for Research Reactor support products and resources is a subject of dynamic needs in other processes or fields of activity and can not be controlled by Research Reactor Owner, subject of risk and uncertainty. Reducing the risk and uncertainty means increase the sustainability.

Maintaining a **diversity of options** in Research Reactor application/utilization may help to avoid losses when one option is reduced or fail. **Innovation in products, services and technology** for efficient utilization of reactor reducing in the same time the radioactive waste and environmental impact is a direction of sustainability of Research Reactors. **Protecting the investments, life extension and maintenance** for research reactors is a factor of sustainability, and an indicator as well. **Radiological protection** by limiting the exposure of staff and population below standards of protection in terms of exposure could be a factor of sustainability, and an indicator as well. Radiation protection is a dynamic field subject of results of R&D and developments of new instrumentation. **Safety** of Research Reactors expressed in specific indicators reinforced by **Safety Culture** of Operating Organization giving an overriding priority to safety issues is the guaranty of sustainability of a given research reactor. **Radioactive waste management** for reactor operation/maintenance and decommissioning and research reactor spent fuel with associated costs and radiation exposure of staff and population may be an important factor of sustainability, and an indicator as well. Sustainable utilization of Research Reactors is based more on knowledge and skills and less on materials, this means valuable human resources. Ensuring **high qualified and licensed staff and Research Reactor operators** is a factor of sustainability, and an indicator as well. International cooperation and synergy is a valuable resource for Research Reactors sustainability by exchange and reciprocal support, cooperation agreements alliances, initiative, networking in order to enhance the capability of collective sustainability and reliability of products and services with less financial effects. Role of government policy in the area of energy, research and development is essential where research reactors are state owned. The role of government is essential in formatting regulatory framework and policies that will allow a coherent approach toward decommissioning of nuclear facilities and disposal of radioactive waste.

Sustainable nuclear activities developed by Research Reactors have to achieve a high level of public acceptance from community consideration and involvement in decisions concerning environmental issues.

2. Sustainability of TRIGA 14 MW Research Reactor in Pitesti, Romania

Sustainability of of TRIGA 14 MW Research Reactor could be defined as the ability to maintain safe and economic operation of reactor for the next twenty years. The relative long term of operation target for 50 years in total since commissioning is an objective which was accomplished by several other research reactors. In case of 14 MW TRIGA, this objective could be achieved by:

1. management of ageing equipment systems and instrumentation so the research reactor life time could be safely extended for the next twenty years
2. human resources management, training and retraining and continuous employment of replacements in order to reduce the mean age of reactor staff from 48 years to 30 - 32 years old.
3. ensuring solutions and experimental devices for new application on material testing and preparation of testing activities for the newly designed European research reactors and sharing experience and know-how through international cooperation.

3. Vision

The reactor will be a safe and reliable neutron source for material testing, for research in the field of nuclear safety of power plants for at least 20 years and contributing to radioisotopes market especially fission ^{98}Mo from LEU.

4. Strategic approach of issues which may impact the sustainability.

4.1. Operation of Research Reactor

To ensure the resources for operation, mainly:

- human resources sufficient in number and qualification to ensure four shifts operation and replacement licensed by Regulatory Authority
- fresh fuel supply for extended operation was ensured in the framework of IAEA-TC Project by contribution of IAEA, US-DOE through GTRI and by qualification of and European nuclear fuel provider. The core conversion was successfully performed on 12 May 2006, achieving a strategic goal established some 15 years ago. The spent fuel containing HEU, as well as unirradiated HEU was shipped in the country of origin.
- To secure founds for fuel and for continuous operation, maintenance and spare parts, founds for modernization of reactor systems and instrumentation and control were obtained through IAEA-TC Project and from government
- Keeping the licensed operational facility

4.2. Cost of operation / Cost recovery

Yearly budget of TRIGA Research Reactor facility provide funds for covering the reactor operation including expenses for safety, maintenance, plant life extension and other taxes.

The yearly budget contains provisions for staff salaries, expenses with water, electric power, heating, radioactive waste transfer, conditioning and disposal, spent fuel management during intermediate storage, materials for maintenance and operation, expenses with communication, and for other services at the level of institute as physical protection, fire brigade, radiation protection and monitoring of facility and site.

Assets depreciation, costs recovery over designed life period including cost of modernization are distributed over life extended period. An important cost factor is taxes and licenses fees and contribution to decommissioning founds.

The cost of operation per hour could be computed and the cost for applications/users could be established in order to recover the expenses. The economic viability of research reactor is a strategic issue. Costs are justified and verified by the top management. Safety and economic viability are complementary issues. Developing yearly programs and plans that enhance economics also are likely to be benefic for reactor safety. This could be expressed as a well used research reactor and is safer that a shutdown one.

4.3. Licensing and regulatory aspects

Licensing concerns reactor facilities, some category of operational staff, new experiments, new products and services provided by Operating Organization, Renewing the licenses every two years is a regulatory requirement in Romania.

4.4. Quality Management, Health, Safety and Environment

Institute Integrated Management System was certified by Lloyd’s Register Quality Assurance for quality management system, for environmental management system, for occupational health and safety management system, according to the current standards.

The institute Quality Management System was authorized by National Commission for Nuclear Activities Control in Romania. The Quality Management System in institute is applicable to all processes which lead to performance of nuclear activities starting with design of nuclear equipment, installations, manufacturing, control, including among many others operation of nuclear installations (Research Reactor, Post Irradiation Examination Laboratory, Radioactive Waste Station, transportation of radioactive sources and materials).

4.5. Technical cooperation and information exchange

A large contribution of achievements of research reactors of Romania is due to technical cooperation with IAEA-TCEU and with departments of Research Reactors Nuclear Safety and physics sections. International meetings with specific topics of research reactor safety and utilization enhanced the communication and information exchange. Participation in US-DOE Project Sister Laboratories improved strategic approach of activities development and business orientation. Participation in the European Framework Research Projects, for MTR+I3, open new perspectives for TRIGA Research Reactor utilization for development of some application that in the future will be used in Jules Horovitz Research Reactor in France.

4.6. Life Limiting Factors

Following the provisions of Feasibility Study the last four years were dedicated to reactor modernization in order to increase the nuclear safety and utilization capacity. The obsolescence of nuclear safety instrumentation of reactor as well some equipments in auxiliary system was remediate through a large investment project which was commissioned in December 2009.

4.5. Organizational Structure

The Research Reactor Department is integrated in the institute structure where the same level of authorization and accreditation is applied for other departments. For this reason, Research Reactor Department is responsible for operation and maintenance, many other functions are accomplished in other departments as radioprotection and site monitoring, emergency preparedness, metrological calibration of instruments, periodic inspection and verification, physical protection, quality management and accountancy.

4.6. Personnel Development

Due to some administrative regulations, the maximum number of staff employees in institute is almost constant since ten years ago. In these conditions, the employment of young engineers, scientists or professionals is very difficult, leading to constant ageing of personnel. Training in specific areas for research reactor operation takes 3 years and this period is followed by examination and licensing by Regulatory Authority. Ensuring licensed staff in a quite large time span suppose another type of strategic approach.

5. Management of strategies

Management of strategies for sustainability of research reactor is attribute of institute as Operating Organization.

The major objectives which management believes that will enhance sustainability of 14 MW TRIGA Research Reactor in Pitesti are:

- Safety of nuclear installations
- Increasing the level of utilization for institute and abroad users
- Preserving the professional competence of staff threaten by depreciation by ageing and loss of experience
- Protecting the environment
- Promoting Safety Culture, Quality Culture, Organization Culture among all staff and of organization. **Sustainability comes and goes with culture and morality**.

All above become objectives of Integrated Quality Management annual planning for which specific actions and responsibilities are assigned and performance and planed performance indicator are attributed.

6. Performance Indicators

Performance indicators allow measurement of sustainability and progress evaluation. Performance indicators could be qualitative or quantitative, some indicators as number of hours of reactor operation, number of irradiated samples are quantitative, others are expressed in percents of accomplishment, and those could be subjective/qualitative. The system of indicators is stable for several years in order to measure progress, to observe the latent weaknesses and to set preventive measures against degradation of sustainability. Performance indicators are also subject of continuous improvement to reduce subjective evaluation and incertitude for long term evaluation.

7. Reporting and communication of achievements

All activities related to sustainability are inspected, controlled and audited by designated inspectors, auditors, which establish reports on inspected activities and dispositions or corrective actions in real time. Annual analysis performed by management allow on the basis of a yearly report made by process responsible persons to evaluate the achievements on sustainability. Communication of achievements across organization allow the evaluation of objectives accomplishment in areas concerning safety, level of utilization and finances, status of licenses for staff and facility, environmental threat and satisfaction of client and stack holders.

8. Conclusions

Sustainability in the context of Research Reactors is defined as the ability to keep equilibrium between utilization and depreciation of complex system of resources and capacity which sustain the role of Research Reactors in production of products and services for other processes which on theirs turn should be sustained. As a general rule, sustainability trends and drivers depends on:

- Social factors – social system we live
- Technological factors – how technology change the industrial environment
- Economical factors – impact on financial system, access to finances
- Environmental factors – monitoring/reducing impact on resources consumption, waste generation, health and risk
- Political factors – political system and policy regulation/legislation

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THE IAEA ACTIVITIES TOWARDS ENHANCED UTILISATION, SUSTAINABILITY AND APPLICATIONS OF RESEARCH REACTORS

D. RIDIKAS[1], P. ADELFANG[2], K. ALLDRED[2], E.E. BRADLEY[2], I.N. GOLDMAN[2*],
A. KHVAN[1,2], G. MANK[1], N. PELD[1,2]

International Atomic Energy Agency
[1]Division of Physical and Chemical Sciences (NAPC)
[2]Division of Nuclear Fuel Cycle and Waste Technology (NEFW)
Wagramer strasse 5, PO Box 100, 1400 Vienna, Austria

ABSTRACT

This paper will give a brief introduction to the programmatic structure of the Research Reactor (RR) related activities of the IAEA sub-programme "Research Reactors", under which the project on "Enhancement of utilization and applications of RRs" will be presented in more detail. Both recent achievements and future planed actions will be reported with the major emphasis on RR utilisation related issues, specific applications of RRs, networks and coalitions, and assistance to the Member States (MS) planning their 1st RR.

1. Introduction

Research reactors (RRs) have played and continue to play an extremely important role in the development of nuclear science and technology. They are used to produce medical and industrial isotopes, for research in physics, biology and materials science, and for scientific education and training. They also occupy an indispensible place in nuclear power programmes. For nuclear research and technology development to continue to prosper, RRs must be safely and reliably operated, efficiently utilised, refurbished when necessary, provided with adequate non-proliferating fuel cycle services and safely decommissioned at the end of life. From more than 670 RRs (including critical facilities) constructed around the world, in February 2010, 234 were still operating, while 11 were under the status of "temporary shut down" [1]. Russia has the highest number of operational RRs (48), followed by USA (41), China (15), Japan (13), France (11) and Germany (10). The RRs are distributed over 56 Member States (MS), including 40 developing countries. Of the RRs that are no longer operating, some of them have plans to resume operation in the future, some are undergoing decommissioning or waiting to be decommissioned, but some others are in an extended shutdown state with no clear plans for their future.

2. RR Issues and trends

Today the decreasing and rather old fleet of RRs world-wide (see Fig. 1) faces a number of critical issues and important challenges such as underutilization, non-existent or inappropriate strategic business plans, aging and needs for modernization-refurbishment, the presence of fresh or spent HEU fuel, unavailability of qualified high-density LEU fuels, accumulation of spent nuclear fuel, needs for advanced decommissioning planning and implementation stages, and, in some cases, safety and security issues. In addition to this non-exhaustive list of challenges are the plans to build new RRs by MSs with little or no experience in this domain.

As about 70 % of the operating RRs in the world are over 30 years old (Fig. 1, right panel), nowadays **RR ageing management**, modernization and refurbishment are key driving issues. One should note separately that these old facilities include the five reactors that produce the bulk of the world's supply of ^{99}Mo! Planned Agency activities related to RR

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[*] Lantheus Medical Imaging, N. Billerica, MA, USA; since October 2009.

ageing management, modernization and refurbishment have been advanced and will continue in the future actions (see Section 3). In close cooperation with the activities covered by another sub-programme “Safety of Research Reactors”, such efforts will help to maximize the availability and reliability of these facilities and subsequently the supply of isotopes important to human health.

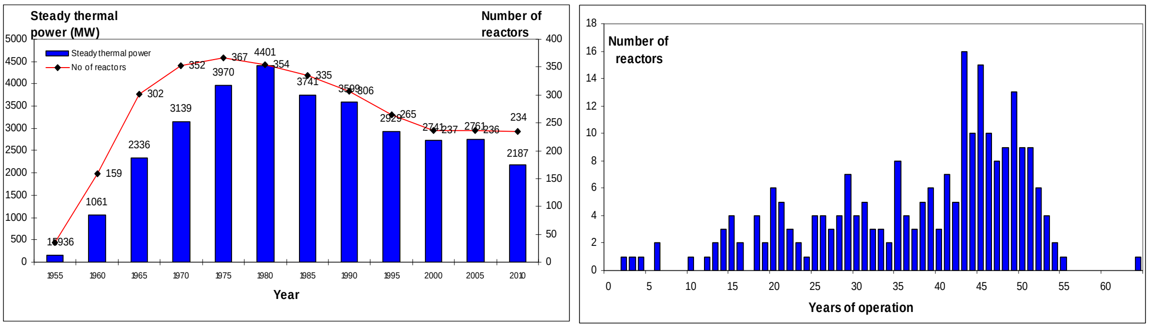


Fig 1. Left: Time evolution of the number of RRs and their thermal power. As of February 2010, there were 234 RRs in operation with their total power close to 2.2GW$_{th}$. Right: Age distribution of operational RRs. 70 % and 50 % of all RR fleet are older than 30 and 40 years respectively.

Another important issue is that, although the number of RRs is steadily decreasing, more than 50% of operational **RRs are still heavily underutilized** and operate less than 4 FPW/year (see Fig. 2). Given the projected decrease in RRs from 234 today to between 100 and 150 in 2020, greater international cooperation will help to assure broad access to such facilities and their efficient use. Therefore, there is currently a substantial need to develop strategies for RR effective utilization on a national, regional and international basis for a significant number of these facilities.

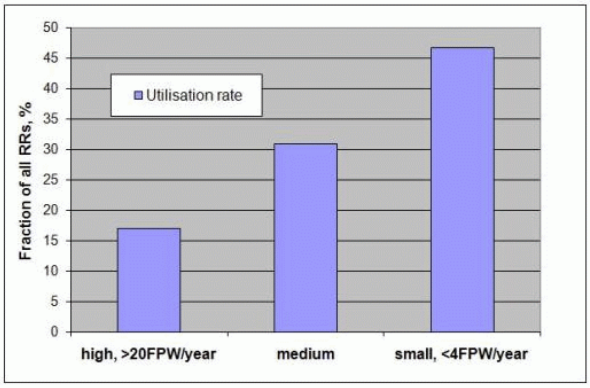
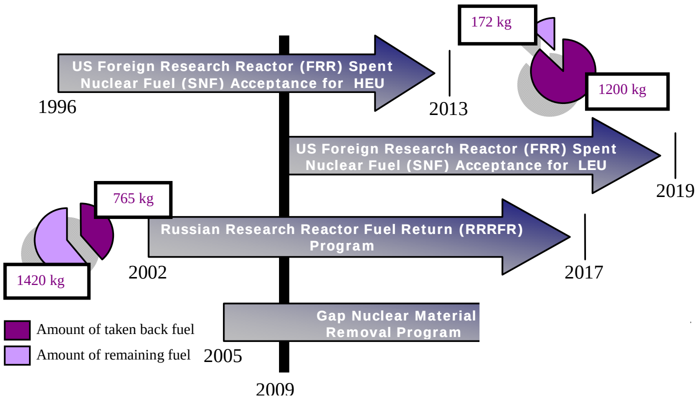


Fig 2. Occupation rate of RRs (including critical assemblies). Nearly 50 % of all RR fleet are operating less than 4 FPW/year (FPW - Full Power Week, 7 days times 24 hours).

The above RR underutilisation issue is somewhat in contradiction to the recently increased number of **requests and plans to build new RRs** (e.g. Azerbaijan, Jordan, GCC countries, and Sudan), which in many cases is viewed as an intermediate step towards establishment of a future nuclear power programme. In this context, sharing resources is crucial in order to increase utilization on the one hand and on the other hand to pave the way for the decommissioning of underutilized ageing reactors. It also serves to help preserve knowledge base and human resources and, at the same time, ensure the safe and sustainable operation of RRs worldwide.

Last but not least, the **reduction of Highly Enriched Uranium (HEU) fuel used by RRs** including ongoing take back programmes of spent fuel remains one of the priority activities of the IAEA. This includes core conversion from HEU to LEU, isotope production target conversion from HEU to LEU, and repatriation of RR fuels (both fresh and spent) to the country of origin. Thanks to an international cooperation involving 130 countries and stimulated by the creation in 2004 of the Global Threat Reduction Initiative (GTRI), 67 RRs have already been converted or shutdown prior to conversion to an LEU core and another 35 await conversion with existing LEU fuel. Another 27 RRs are waiting for the development of a new generation fuel based on very-high density Uranium-Molybdenum alloy, and on which the international research efforts are now focusing. It is expected that all HEU RRs are converted to LEU or shutdown by 2018, which is close to the deadline for the fuel "take back" programme as shown in Fig. 3 [2].

Fig. 3: Current and planned status of the fuel take back programmes [3].



In response to the above challenges, the IAEA is taking action and designing activities to tackle these issues and make sure that promotion, support, and assistance to Member States in the development and uninterrupted operation of strong, dynamic, sustainable, safe, and secure RRs dedicated to peaceful uses of atomic energy and nuclear techniques is preserved. The IAEA has taken the initiative in this direction by organising expert meetings and workshops, encouraging collaboration through coordinated research projects, publishing state-of-the-art technical documents as well as assisting MS through national and regional Technical Cooperation (TC) projects. In addition, through strategic planning and allied support, the IAEA is assisting MS without RRs to become part of RR coalitions or networks [3] as a first step to develop their national capabilities and at the same time improve all aspects of utilization and modernisation of existing RRs, and therefore, sustainability and innovation.

Although IAEA has been playing a lead role in all these areas under the corresponding sub-programmes (see Section 3), this paper will concentrate mainly on the ongoing IAEA project "Enhanced Utilisation and Applications of RRs" [4]. Both recent achievements and future planed actions will be reported with the major emphasis on RR utilisation related issues, specific applications of RRs, networks and coalitions, and assistance to the MS planning their 1st RR.

3. Programmatic Structure of RR Related Activities

The RR activities at the IAEA are mainly implemented through two sub-programmes. The first sub-programme, known as "Research Reactors", covers RR utilization aspects, fuel issues, including infrastructure, operation and maintenance. The second sub-programme, known as "Safety of Research Reactors", covers the safety aspects of RRs. The objectives of each sub-programme are accomplished through specific projects that are included in the biennial plans or so called "Blue Book". Presently active four projects within the sub-programme "Research Reactors" are shown in Fig. 3. It is seen that the sub-programme maintains focus on the different facets of RRs, such as effective utilization, improvement of the capabilities of MSs for planning new and innovative reactors, the back end of the fuel cycle and the technological and engineering aspects of operation and ageing management. One notes separately that different Technical Cooperation (TC) activities are supported within the corresponding projects.

As long as the 1st project is concerned (see Fig. 3), over the years the focus of IAEA work has been gradually changing: from the traditional support of fundamental research and training to helping RR facilities with strategic planning and sustainability to increase utilisation in more commercial areas. Renewed interest in nuclear power, the worldwide expansion of diagnostic and therapeutic nuclear medicine, extensive use of semiconductors, advanced neutron imaging and other neutron beam techniques in the automotive and aeronautic industries or fuel cell development presents new opportunities for operational RRs – including providing services to countries without such facilities. In this new context regional and interregional thematic collaborations, networking and centres of excellence for enhanced utilization of RRs were initiated and supported, resulting in recent Research Reactor Coalitions (RRC) efforts.

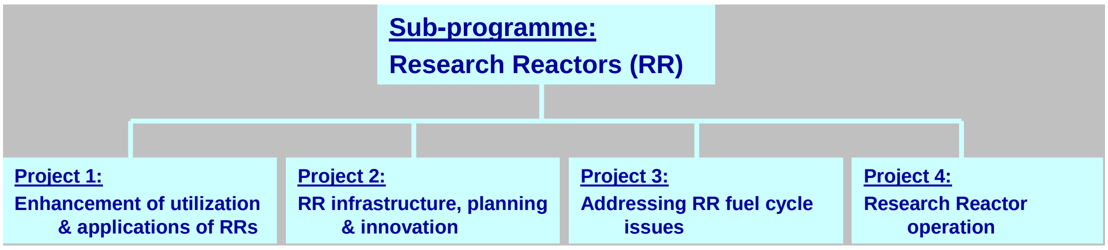


Fig 3. Programmatic structure of RR activities under the sub-programme “Research Reactors”.

4. RR Coalition and Network Projects

RR Coalitions and Networks presently promoted and supported by the IAEA [3] aim at consolidation of the international/regional RR sector by establishing grouped entities to serve as international/regional user centres. In this way, countries/regions that do not have RRs or are considering closing an old reactor can gain access to nearby facilities which have up to date technical capabilities including high levels of nuclear safety and security. It is expected that MSs will increasingly need Agency assistance in strategic planning and institutional arrangements for possible national and regional RR coalitions, networks and shared-user facilities. The Agency support is ensured both through the regular budget and extra-budgetary contributions, including ongoing regional Technical Cooperation (TC) projects.

In 2007-2009, with the assistance of the IAEA a number of RR coalitions have been formed in Eastern Europe (EERRI), Baltic Sea (BRRN), EurAsia (EARRC), and Caribbean (CRRC) regions and more are being discussed (e.g., the Mediterranean, Asia/Pacific, African regions,…). These cover different areas for collaboration, including radioisotope production, neutron activation analysis, fundamental research, education and training activities, radioactive waste management, etc. as schematically presented in Fig. 4.

The Agency’s role in this area is to serve as a catalyst and a facilitator of ideas and proposals. Plans for the short term future seek to consolidate the existing coalitions and to encourage maturation, self-reliance and sustainability, new business/utilization activities, and participation by countries without ready access to RRs. Work will also continue on other prospective coalitions that have been under discussion. In particular, the ongoing crisis and unreliability of supply in the international isotope market – especially relating to Mo-99 – has offered a potential opportunity for new irradiation and processing capabilities which could ideally be satisfied through a coalition of producers. The same applies for the increased needs in education and training in the MS aiming at expanding or newly developing nuclear power programmes as part of their mixed energy share.

Although some noticeable results have been obtained in initiating and supporting RR coalitions [3], much more work needs to be accomplished in order to achieve the objective of increase utilization of individual RRs through collective effort, on a self-sustainable and self-reliant basis. In addition to their individual strategic plans, the coalition partners need to put into place coalition-based common strategic and management plans as a group. They also need to pursue more detailed market analysis and business development to identify specific pay-back opportunities through sustainable commercial activities, through complementary marketing and delivery of irradiation products and services, education and training among other revenue generating applications of RRs.

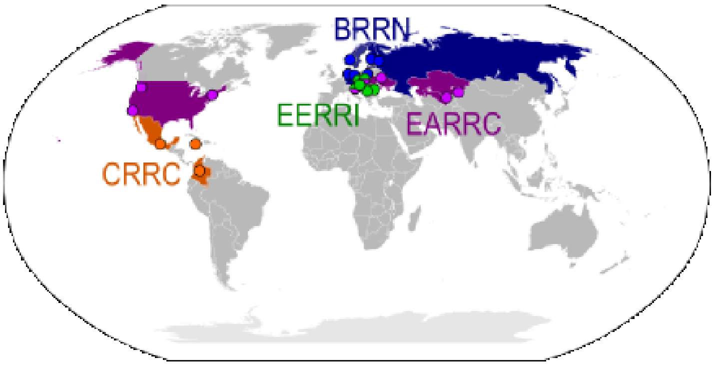


Fig 4. IAEA supported RR coalitions and networks (see the text for details).

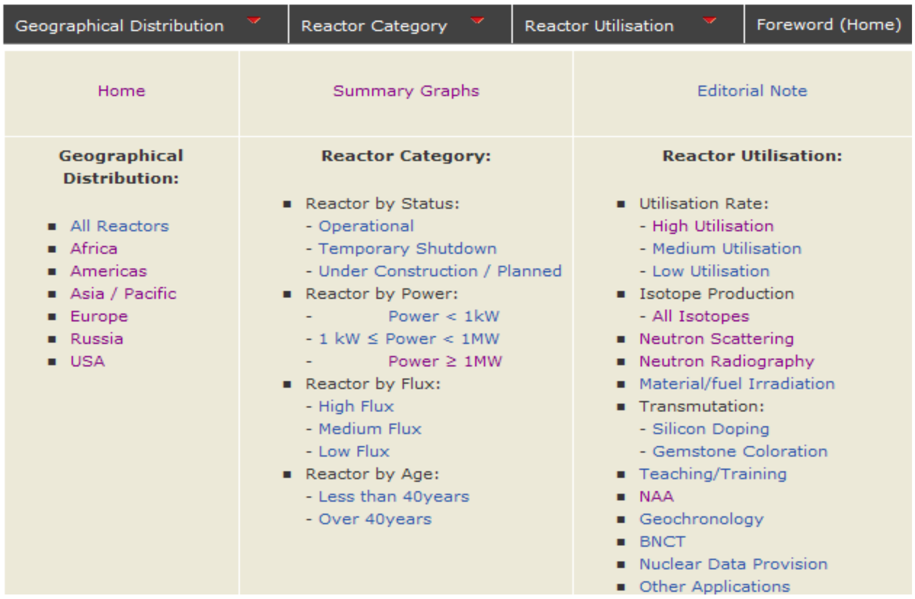
5. IAEA Research Reactor Data Base

The IAEA department of Nuclear Science and Applications (NA) and the department of Nuclear Energy (NE) jointly manage a Research Reactor and Spent Fuel Database (RRDB) [1]. This database serves to promote the capabilities of individual facilities as well as help IAEA internal and external stakeholders plan and develop programmatic activities in response to the expressed needs of individual MS. The complete IAEA RRDB contains the information on both operational, planned, shutdown and decommissioned RRs. It is prepared from the data provided by RR administrators of the MS through annual questionnaires. While every attempt is made to keep the RRDB current, the IAEA makes no guarantees, either express or implied, concerning the accuracy, completeness, reliability, or suitability of the information. Therefore, national RR data providers or individual RR managers are asked to inform the RRDB Project Officers of any updates or corrections needed.

In the promotion and support and the peaceful, efficient and sustainable uses of RRs, recently the IAEA has developed a dedicated Operational RR Data Base (ORRDB) being a specific output of the IAEA computerised RRDB [1]. The table of contents for this new ORRDB is shown in Fig. 5. It contains only the information related to the operational RR facilities and classifies them into three major categories according to a) geographical location, b) reactor characteristics/features, and c) reactor utilisation and applications. Thanks to the pre-designed classification filters, some useful statistical information can be easily found relevant to all operational RRs, including lists of the facilities providing specific applications, i.e. products and services as isotope production, activation analysis, teaching and training, etc. In addition, the ORRDB also includes all detailed technical information reports of the individual facilities. Finally, although the ORRDB is available on internet [5], it can also operate off line and occupies less than 10MB of disk space.

This new utilisation and application driven ORRDB provides IAEA MS with a resource to assist efforts in developing strategies for capacity building, effective utilization and management of RRs on a national, regional and international basis. It also contains somewhat “sensitive” information like the utilisation rates of both individual RRs as well as country-averaged statistics. It is expected that this new ORRDB, in addition to standard book-keeping, should help in enhanced and more efficient utilization of RRs in MSs for many practical applications, facilitate cooperation between different RR centres, and promote networking both for RR host and non-host MSs. The responsible Project Officer would appreciate all MS' input how this new tool could be improved further to achieve targeted objectives.

Fig 5. Table of contents of the dedicated Operational RR Data Base (ORRDB) [5].



Home	Summary Graphs	Editorial Note
Geographical Distribution: ▪ All Reactors ▪ Africa ▪ Americas ▪ Asia / Pacific ▪ Europe ▪ Russia ▪ USA	**Reactor Category:** ▪ Reactor by Status: - Operational - Temporary Shutdown - Under Construction / Planned ▪ Reactor by Power: - Power < 1kW - 1 kW ≤ Power < 1MW - Power ≥ 1MW ▪ Reactor by Flux: - High Flux - Medium Flux - Low Flux ▪ Reactor by Age: - Less than 40years - Over 40years	**Reactor Utilisation:** ▪ Utilisation Rate: - High Utilisation - Medium Utilisation - Low Utilisation ▪ Isotope Production - All Isotopes ▪ Neutron Scattering ▪ Neutron Radiography ▪ Material/fuel Irradiation ▪ Transmutation: - Silicon Doping - Gemstone Coloration ▪ Teaching/Training ▪ NAA ▪ Geochronology ▪ BNCT ▪ Nuclear Data Provision ▪ Other Applications

6. Summary

RRs have played and continue to play an important role within several fields of basic science, in the development of nuclear science and technology, in the valuable generation of radio-isotopes and other products for various applications, in support of nuclear power programmes, including the development of human resources and skills. Nowadays the decreasing fleet of these facilities faces a number of critical issues and important challenges such as underutilisation, inexistent or inappropriate strategic-business plans, ageing and needs for modernization-refurbishment, presence of fresh or spent HEU fuel, unavailability of qualified high-density LEU fuels, accumulation of spent nuclear fuel, advanced decommissioning planning and implementation stages, and, in some cases, safety and security issues. In addition to this non-exhaustive list of challenges are the plans to build new RRs by MSs without no or little experience in this domain. In response to these challenges, the IAEA is taking action and designing activities to tackle these issues and make sure that promotion, support and assistance to MSs in the development and uninterrupted operation of strong, dynamic, sustainable, safe and secure RRs dedicated to peaceful uses of atomic energy and nuclear techniques is preserved.

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U-TARGET IRRADIATION AT FRM II AIMING THE PRODUCTION OF MO-99 – A FEASIBILITY STUDY

H. GERSTENBERG, C.MÜLLER, I. NEUHAUS, A. RÖHRMOSER
Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II)
Lichtenbergstrasse 1; D-85748 Garching - Germany

ABSTRACT

Following the shortage in radioisotope availability the Technische Unversität München and the Belgian Institut National des Radioéléments conducted a common study on the suitability of the FRM II reactor for the generation of Mo-99 as a fission product. A suitable irradiation channel was determined and neutronic calculations resulted in sufficiently high neutron flux densities to make FRM II a promising candidate for Mo-99 production. In addition the feasibility study provides thermohydraulic calculations as input for the design and integration of the additional cooling circuit into the existing heat removal systems of FRM II. The required in-house processes for a regular uranium target irradiation programme have been defined and necessary upgrades identified. Finally the required investment cost was estimated and a possible time schedule was given.

1. Introduction

Tc-99m is by far the most widely used radioisotope in nuclear medicine. Its low gamma energy and its short half life of only 6 h make it an ideal probe for diagnostic imaging of many human organs.

The most common way for the production of Tc-99m requires the irradiation of uranium targets leading to the generation of Mo-99 the mother isotope of Tc-99m which itself has a relatively short half life of 66 h too. Consequently neither Mo-99 nor Tc-99m can be stockpiled for weeks or longer. On the other hand at present only three European research reactors are equipped with facilities allowing the irradiation of uranium targets for the production of the medical isotopes mentioned above. In addition, all of these reactors are in operation since several decades and turned out to become vulnerable against malfunction. This situation led to a serious shortage for medical isotopes in 2008 and consequently a growing public awareness for the reliability of their supply [1].

Already before the shortfall of Mo-99/Tc-99m the Belgian Institut National des Radioéléments (IRE) and the Technische Universität München (TUM) agreed to cooperate on a feasibility study dealing with the possible use of TUM´s research reactor FRM II for the irradiation of IRE's uranium targets. The study was completed in mid 2009 and provided promising results.

2. General Boundary Conditions

The Forschungsneutronenquelle Heinz-Maier-Leibnitz (FRM II) is a 20 MW heavy water moderated, light water cooled research reactor being operated since 2005 by the TUM on its campus in Garching close to Munich. The basic design feature of FRM II is the single cylindrical compact fuel assembly forming the entire reactor core. Typically FRM II is run in cycles of 60 operational days in a row and for up to four cycles per year. Although FRM II has by its design clearly been optimised for basic research by means of beam tube experiments it claims to be a multi purpose reactor offering already presently several irradiation facilities [2, 3]. All of their irradiation channels are located within the heavy water moderator tank but hermetically separated from the heavy water itself by means of a water tight flange. In addition they are all accessible from the working area around the reactor pool for loading and unloading during reactor operation. These features had been transferred as an imperative condition for the target irradiation facility under investigation.

The feasibility study was a cooperative effort between TUM and IRE. Consequently the study was a based exclusively on IRE's target design, i.e. tubular targets containing 4.0 g of highly enriched uranium (HEU ≤ 92.2% in U-235) with a total height of 160 mm and an outer diameter of 22 mm.

3. Design of the Future Irradiation Facility

3.1 Irradiation Channels

In the first step after the launch of the study various spare positions within the heavy water moderator tank of FRM II were examined with respect to their suitability for being allocated to the irradiation of uranium targets. The most promising candidate is a vertical thimble being located in a distance centre to centre of 450 mm from the reactor core. It was originally foreseen to be used in a fast rabbit irradiation facility which, however, had never been built. Unfortunately the existing thimble reaches only down to the mid plane of the reactor core. In order to use the entire height of the fuel assembly and to irradiate as many targets as possible in parallel it will be replaced by a new, longer thimble going down to the bottom of the reactor core. In addition the new thimble will be manufactured from zircalloy instead of AlMg3 in order extend its lifetime considerably.

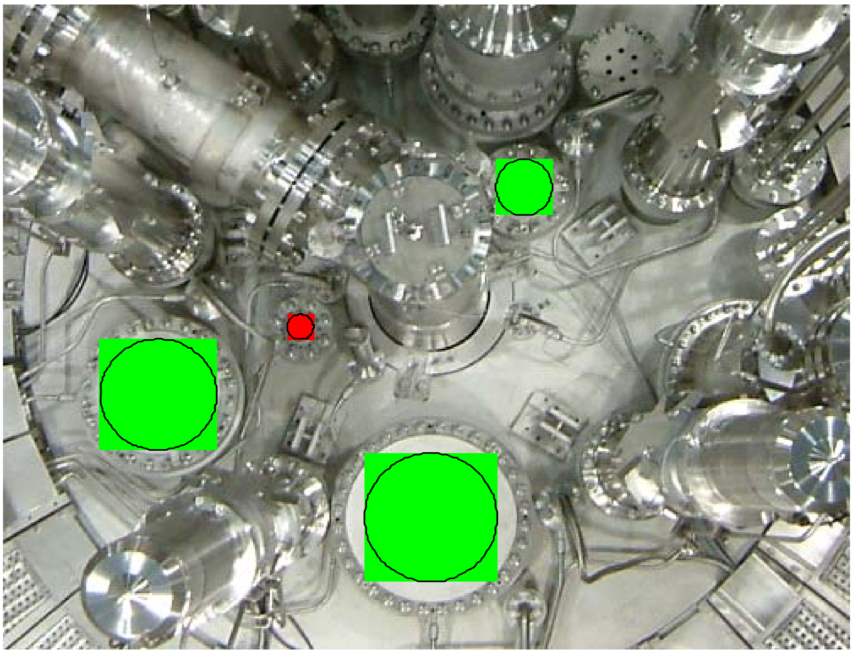

Fig. 1:
Top view to FRM II moderator tank. The future uranium target irradiation position is indicated in red, rejected spare positions are indicated in green.

The thimble will be housing three independent irradiation channels, i.e. three tubes containing up to five uranium targets each and a corresponding tube for each of them in order to close the cooling water circuit. The open space within the thimble will be He-filled and the humidity of the He gas will be monitored. This feature will control the leak tightness of the thimble and of its installations as well.

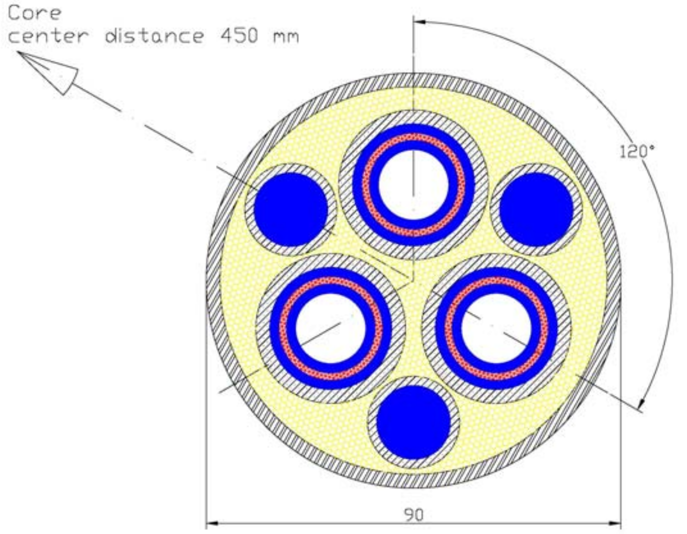

Fig. 2:
Arrangement of targets (red circles), target tubes and cooling water supply tubes within the thimble.

3.2 Neutronic Calculations

A major parameter for the suitability of the irradiation position is doubtlessly the neutron flux density. In the present study it has been examined using the 3d-transport code MCNP [4]. The input model took into account the single fuel assembly arrangement including all technical and experimental installations in the moderator tank and of course the design of the thimble containing the HEU targets described above.

The values of the flux density and their geometrical profiles along the entire irradiation channels (cross sections formed by target, tube and light cooling water) were calculated to be approximately 2.2E14 $cm^{-2}s^{-1}$ in the average with a maximum value in the mid plane of the core close to 3E14 $cm^{-2}s^{-1}$. It is to be remarked that the use of zircalloy for the thimble and, more important, the use of He instead of light water in the open space of the thimble resulted in a gain in neutron flux density. The corresponding heat load resulting from the fission processes in the irradiated targets was estimated to be equal to 430 kW provided that all 15 irradiation positions are taken.

The Mo-99 activity being produced during irradiation is estimated to sum up to 17 kCi right after a typical 6 days irradiation with the maximum number of targets, namely 15, exposed.

In addition to the neutron flux density and power production the neutronic calculations showed that the penalty caused by the target irradiation facility to neighbouring beam tube experiments is marginal, i.e. in the range of about 1%. The same applies to the influence of the targets to the reactivity of the reactor core. It was calculated to be 0.28% for fresh targets and will be even lower after the amount of Xe-135 in the targets will be in the equilibrium. Finally also the transient caused by a sudden drop of a stack of 5 targets due to a technical interference was looked at. The response curves for several sink velocities were calculated. In order to get a realistic scenario for that kind of incident a mock-up of the irradiation facility is foreseen to be built and used with various designs for target stacks, in particular for the spacers between the individual targets, and different coolant velocities.

3.3 Cooling and Thermohydraulics

As mentioned above the power released by the targets during irradiation was estimated to be approximately 430 kW. Adequate cooling is foreseen to be guaranteed by a system of four pumps. Thus, during irradiation the pump capacity is 4 × 50%; with respect to the after heat removal of the irradiated targets it is increased to 4 × 100%. Two pumps must be able to provide sufficient cooling capacity for the targets but three of them are in operation all the time; the fourth one is only a spare which is taken into operation only in case of a failure occurring in one of the others. This concept has been chosen in order

- To continue reactor operation and target irradiation in case of a failure occurring in a single pump and
- to reliably avoid an emergency shut down of the reactor itself due to a cooling failure within the uranium target irradiation facility.

The proposed cooling circuit is designed to be as far as possible independent from other reactor installations. It will take the water from the reactor pool at a rate of about 6.5 kgs/s and feed it back into the pool at its outlet. The heat removal from the coolant circuit is foreseen to take place in two heat exchangers: one of them supplies 95 kW for the heating of the reactor pool’s warm water surface, which is heated electrically so far, whereas the excess power produced in the targets is transferred into the reactor’s secondary cooling circuit.

Besides the reliable removal of the heat produced within the targets during irradiation the coolant circuit is designed to cover the following safety aspects:

- The target temperature must not exceed 400 °C according to the specification of the manufacturer.
- The pipelines have to withstand the water pressure created by the pumps. A pressure stage of 16 bars for the piping was established to be sufficient.
- The coolant flow has to be guided in bottom → top direction in the irradiation channel and it has to be strong enough to lift the target stack against its weight force in order to reliably avoid an uncontrolled drop of targets into the irradiation position even in case of a defect of the handling tools.

3.4 In House Handling Aspects

In addition to the irradiation technique the handling steps in the periphery – in particular the preparation of freshly irradiated targets for the shipment on public roads – had to be looked at.

Calculations show that after completion of the irradiation the targets have to stay in a water cooled position for a total of about 12 hours - only the first few hours, however, under forced cooling - before they are allowed to be handled in air. After expiry of this decay time the targets are foreseen to be transferred into the hot cell of FRM II which offers direct access from the reactor pool through a hatch in the floor. In the hot cell the targets will be removed from the support which had held them during irradiation and inserted into the transport containers provided by the customer. From the radiation protection point of view the dry packaging procedure is regarded to be considerably advantageous as compared to under water loading in the reactor pool. In addition this procedure will reduce the time consumption for packaging and radioprotection control procedures. Finally the containers need to be brought to the truck lock at the ground floor of FRM II, where the shock absorbers will be mounted.

Several shortcomings have been identified in the analysis of the in house handling of the transport containers. In particular the goods lift between the 4th floor housing the reactor pool and the ground floor has to be upgraded and additional crane capacity has to be provided. On the other hand it has to be noted that the connection of FRM II to the European highway grid is excellent with the nearest exit only 1 km apart from the reactor.

4. Cost Estimation and Time Schedule

The total cost of the design, construction and installation of the uranium target irradiation facility was estimated to be 5.4 M€. This number includes additional personal, supervision by external experts as required according to German regulations and the upgrade of the periphery. Although the local and the federal government as well as the industrial suppliers of medical isotopes recommend unanimously the presented project it is still suffering from a lack of funding. Since, however, an extraordinary long maintenance period at the end of 2010 which is connected with the drainage of the heavy water moderator tank offers the rare chance to change the thimble in the foreseen irradiation position, TUM nonetheless undertakes at that time to supply the reactor with the necessary zircalloy thimble on its own expense. On the other hand, TUM will hardly be able to finance the entire project from the regular operational budget.

Finally TUM will have to apply at the Bavarian authorities for an extension of the operational license, which so far covers the use of enriched uranium only in form of fuel assemblies and so-called converter plates, i.e. fuel plates for cancer treatment by irradiation with fast neutrons [5]. For this purpose a safety report needs to be written in the first step.

Provided the funding issues will be solved in due time it is foreseen to build the mock-up for the testing of components in summer 2010. With respect to the installations in the reactor pool it has to be noted that access is only possible in the maintenance periods, since in spite of the importance of the project the scientific use of FRM II must not be obstructed by its realization. In summary a realistic estimation of the necessary timeframe predicts the begin of the irradiation service for Mo-99 production at the end of 2013/begin of 2014.

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MO-99 SUPPLY ISSUES : STATUS REPORT AND LESSONS LEARNED

B. PONSARD
BR2 Reactor, SCK.CEN
Boeretang 200, B-2400 Mol – Belgium

ABSTRACT

The worldwide supply of ^{99}Mo relies on a limited number of research reactors and processing facilities. Its production is essential for the nuclear medicine as ^{99m}Tc, obtained from ^{99}Mo/^{99m}Tc generators, is used in about 80% of the diagnostic nuclear imaging procedures. These applications represent yearly approximately 30 million examinations worldwide. The short half-life's of ^{99}Mo (66 hours) and its daughter ^{99m}Tc (6 hours) require a regular supply of ^{99}Mo/^{99m}Tc generators to hospitals or central radiopharmacies. Currently, there are only five nuclear reactors involved in the production of ^{99}Mo on industrial scale: NRU (Canada), HFR (Netherlands), BR2 (Belgium), OSIRIS (France) and SAFARI (South Africa). They irradiate highly enriched uranium targets for the production of about 95% of the available ^{99}Mo by four processing facilities: AECL/MDS NORDION (Canada), COVIDIEN (Netherlands), IRE (Belgium) and NTP (South Africa). However, these ageing reactors are subject to unscheduled shutdowns and longer maintenance periods making the ^{99}Mo supply chain vulnerable and unreliable. Several severe disruptions have been experienced since the fall 2005 due to the occurrence of problems at different stages of the supply chain: reactor outages, release of activity from processing facilities, recall of ^{99}Mo/^{99m}Tc generators by the manufacturers, … It is not expected that the situation will improve significantly in the near future. Therefore, several workshops have been organized in 2009 by the OECD Nuclear Energy Agency (NEA), the International Atomic Energy Agency (IAEA) and the Association of Imaging Producers and Equipment Suppliers (AIPES) to define measures that should be taken to secure the ^{99}Mo supply in the short, medium and long term. This paper summarizes the current status of the ^{99}Mo supply, discusses the ongoing plans for additional ^{99}Mo production capacity and outlines the issues for a reliable global supply chain.

1. Introduction

Radioisotopes are playing a key role in 'in vivo' nuclear medicine procedures for diagnosis (90%) and therapy (10%). The radioisotopes used for 'in vivo' diagnostic purposes are linked to specific chemical compounds to produce radiopharmaceuticals which allow the desired specific physiological processes to be examined (heart, thyroid, liver, kidney, blood flow, …), the detection of tumours (breast cancer, prostate cancer, …), bone scintigraphy, … They must emit gamma rays of sufficient energy to escape from the body so that they can be detected by a camera that will produce an image. Moreover, their half-life must be long enough to allow for logistic and preparations before imaging can occur, and short enough for it to decay during the imaging procedure and disappear soon after it is completed.

Technetium-99m, the daughter of Molybdenum-99, is the most suitable radionuclide for SPECT (Single Photon Emission Computed Tomography) imaging technique with a single 140 keV gamma-ray emission and a very convenient half-life of 6 hours. It is used in about 80% of all diagnostic nuclear imaging procedures, representing yearly approximately 30 million examinations worldwide: 16 million in North America, 7 million in Europe, 6 million in Asia (Japan mainly) and 1 million in the rest of the world [1]. This percentage is expected to continue to grow due to its availability from the very convenient and cost-effective ^{99}Mo/^{99m}Tc generator. Other radioisotopes used in radiodiagnostic procedures are ^{201}Tl, ^{123}I, ^{131}I, ^{111}I, ^{81m}Kr, ^{18}F and ^{68}Ga. In situation of ^{99}Mo shortages, the use of alternative isotopes is boosted and present some disadvantages: for example, ^{201}Tl (73 hours half-life) gives lesser quality images than ^{99m}Tc and the patients are exposed to higher radiation doses.

2. Mo-99 global supply chain

^{99}Mo is characterized by a half-life of 66 hours and is currently mainly produced in research reactors by fission of ^{235}U from high enriched uranium (HEU) targets. There are only five nuclear reactors involved in this production on industrial scale: NRU (Canada, start operation 1957), HFR (Netherlands, start operation 1961), BR2 (Belgium, start operation 1961), OSIRIS (France, start operation 1966) and SAFARI (South Africa, start operation 1965). All these reactors are thus more than 40 years old and are not dedicated to the production of ^{99}Mo. A few additional research reactors meet regional requirements as OPAL (Australia, start operation 2007) and can act as backups on a case by case basis. Unscheduled stoppages of producing reactors are becoming more frequent and last for longer. As a result, supply problems have become more common and more acute since a few years [2].

After an irradiation time of about 168 hours and a cooling period of 12 hours, the irradiated targets are loaded into shipment containers and sent to four processing facilities supplying about 95% of the ^{99}Mo global needs: AECL/MDS NORDION (Canada), COVIDIEN (Netherlands), IRE (Belgium) and NTP (South Africa). The bulk ^{99}Mo is then sent to other companies for the manufacture of the ^{99}Mo/^{99m}Tc generators: COVIDIEN (Netherlands and US), LANTHEUS MEDICAL IMAGING (US), GE-HEALTHCARE (UK) and IBA-MOLECULAR (France). Fig. 1 illustrates the geographical location of the main infrastructures involved today in the ^{99}Mo production.

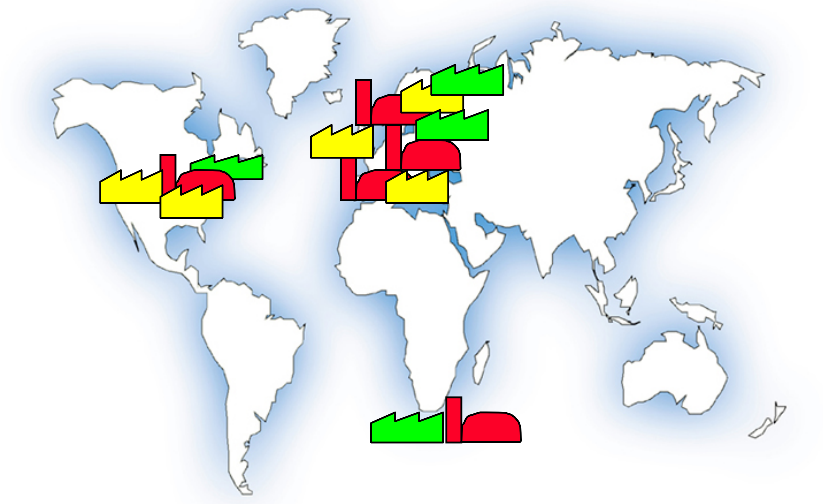

Fig. 1: Mo-99 global supply chain

Finally, the ^{99}Mo/^{99m}Tc generators are supplied to hospitals or central radiopharmacies as shown in Fig. 2 and can be used for only 1 week because of the loss of 1% of activity per hour. In normal circumstances, this strategy of supply allows the availability of ^{99m}Tc every day, 365 days per year, on the basis of a weekly delivery of generators all around the world. Each partner in the supply chain must thus work very efficiently to avoid losing time so that the product can be delivered as quickly as possible, taking shipment constraints into account (by road, by air, …). Nevertheless, the recent supply shortages have highlighted the vulnerability of centering production around a limited number of ageing reactors.

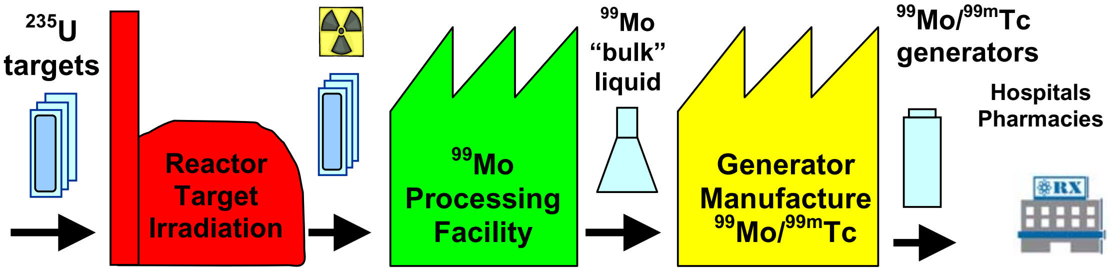

Fig. 2: Mo-99 supply chain

3. Mo-99 global needs

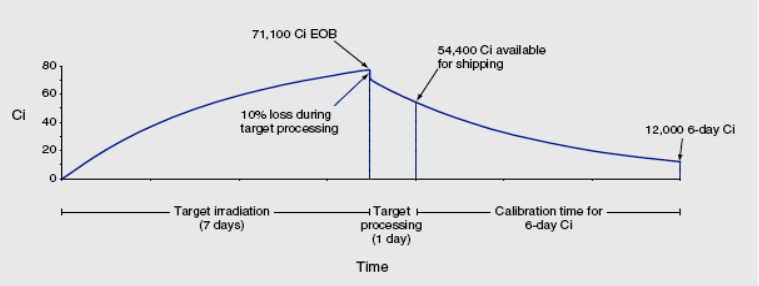

Fig. 3: Mo-99 global needs per week

The weekly requirement of ^{99}Mo worldwide is reported to be approximately 12.000 Ci '6-day' calibrated for North America (53%), Europe (23%), Asia (20%) and the rest of the world (4%). The "6-day curie" is a unit of measure that takes the ^{99}Mo decay rate into account, including the losses during shipments, and represents an average amount of ^{99}Mo that would be available for use 6 days after processing, as illustrated in Fig. 3. The global needs are expected to increase by 3 % per year in the near future. In average, the NRU reactor produces about 35% of the required ^{99}Mo, the HFR reactor about 25%, the BR2 reactor about 15%, the OSIRIS reactor about 5% and the SAFARI reactor about 10% [2]. The remaining ^{99}Mo is produced by reactors for their domestic market.

4. Previous medical radioisotopes shortages

The access to the reactors and processing facilities for the ^{99}Mo has been a matter of concern for the nuclear medicine community for more than ten years. However, new sources of global supply have not been developed because of the expected impact of Canada's MAPLE project involving the construction of two 10 MW reactors dedicated to the production of medical isotopes and of a new processing facility for the supply of ^{99}Mo. Once completed, the reactors could have supplied from 2000 twice the entire global demand for ^{99}Mo but commissioning tests encountered major technical problems and AECL decided to stop the project in May 2008. The limited number of producers worldwide and the limited planning for new capacity can also be attributed to the economic realities of a market in which product pricing reflects subsidized costs due to shared use of government facilities [3]. The risks of global ^{99}Mo supply disruptions increased significantly since 1995 and have been experienced for different reasons as indicated below:

- 1995 : Problems in the shipping of ^{99}Mo due to a strike of Canadian air-flight personnel;
- 1995 - 1997 : Shutdown of the BR2 reactor (21 months) for major refurbishment;
- 1997 : Shutdown of the NRU reactor (5 days) because of a strike;
- 1997 : Definitive shutdown of the SILOE reactor (Grenoble, France) which produced ^{99}Mo;
- 2002 : Shutdown of the HFR reactor (42 days) for reactor operation safety concerns;
- 2005 - 2006 : Recall of ^{99}Mo/^{99m}Tc generators by COVIDIEN (5 months);
- 2006 : Shutdown of the NRU reactor (6 days) for reactor operation safety concerns;
- 2006 : Definitive shutdown of the FRJ-2 reactor (Jülich, Germany) which produced ^{99}Mo;
- 2007 : Recall of ^{99}Mo/^{99m}Tc generators by COVIDIEN (1month);
- 2007 : Shutdown of the HFR reactor (1 month) for reactor operation safety concerns;
- 2008 : Shutdown of the NRU reactor (11 days) for reactor operation safety concerns;
- 2008 : Shutdown of the IRE processing plant (3 months) for ^{131}I release;
- 2008 - 2009 : Shutdown of the HFR reactor (6 months) for operation safety concerns;
- 2009 - 2010 : Shutdown of the NRU reactor (11 months) for reactor vessel welding repairs;
- 2010 : Shutdown of the HFR reactor (6 months) for repair of a primary cooling pipework.

The supply of ^{99}Mo in the year 2010 will again be very challenging because of the extended maintenance periods currently scheduled for 3 of the 5 main reactors involved in the field: NRU, HFR and OSIRIS.

5. Current Mo-99 crisis and status of the main reactors

The NRU reactor (Chalk River, Canada) has been placed in safe shutdown conditions in May 2009 following the detection of a small heavy water leak in the vessel. The Atomic Energy of Canada Limited's (AECL) decided to defuel the reactor to complete vessel inspection and repair activities. Additional work is being conducted to improve the overall reliability of the reactor. According to AECL, NRU will remain offline until April 2010 and the first medical isotopes would be distributed within 10 days after restart. The current NRU license will expire in 2011 and AECL is currently working on license extension issues.

The HFR reactor (Petten, Netherlands) is shutdown since 19th February 2010 for an expected period of 6 months to perform the repair plan of a primary cooling water pipework. Meanwhile, the Nuclear Research and consultancy Group (NRG) plans to build a new reactor, PALLAS, to replace the HFR reactor in 2016. This project will contribute to the production of medical isotopes and ensure the continuation of nuclear research.

The OSIRIS reactor (Saclay, France) will be shutdown for an extended period of about 5 months from June 2010 to undergo major maintenance work for a safe operation until 2015. By that time, the JHR reactor should be able to start its operation in Cadarache to avoid any discontinuity in irradiation facilities in France.

The BR2 reactor (Mol, Belgium) - Fig. 4 - will operate an extra period dedicated to the ^{99}Mo production (6 operating cycles instead of 5 as initially scheduled) in 2010. This has been made possible by extra financial contributions from the industry. In addition, BR2 will be able to offer an increase of its irradiation capacity for the ^{99}Mo production by 50% from April 2010 through the installation of additional new equipments. The reactor is scheduled to operate at least until 2016 and SCK•CEN is already looking at the technical and safety aspects to extend its potential operation until 2026. Another new multipurpose irradiation facility, MYRRHA, a multifunctional accelerator driven subcritical system (ADS) should be able to replace the BR2 reactor in 2022 to perform research programmes and commercial activities including the ^{99}Mo production.

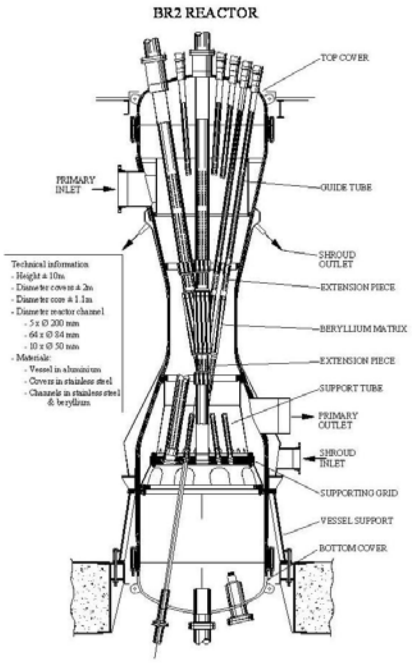

Fig. 4: BR2 reactor

The SAFARI reactor (Pelindaba, South Africa) has no major maintenance work scheduled in 2010 and will be able to continue its supply of ^{99}Mo.

The representatives of the 'Reactor and Isotopes' Working Group of the Association of Imaging Producers and Equipment Suppliers (AIPES) made once again their best efforts to achieve an optimal coordination of the available reactor operating periods in 2010 taking the information above into account. They defined a suitable reactor operating calendar which should minimize the impact of the ^{99m}Tc shortage for the patients, assuming that the NRU reactor would come back on power in April 2010 as announced by AECL and that HFR reactor's shutdown will not be longer than six months as announced by NRG. The operating schedule for 2010 includes a supplementary cycle from the BR2 reactor (Belgium) and two rescheduled cycles from the OSIRIS reactor (France) in the first semester. As a result of coordination efforts, the expected periods of ^{99}Mo production capacity limitations have been reduced from 14 weeks initially to 4 weeks in 2010 (in May, June and July). It is also expected that extra backup supply will be provided from March 2010 through a collaboration between COVIDIEN and the MARIA reactor (Świerk, Poland). Nevertheless, 2010 will be a difficult year where, on average, only 70 - 80% of the ^{99}Mo global demand will be met.

6. Lessons learned

Several organizations under which the OECD Nuclear Energy Agency (NEA), the International Atomic Energy Agency (IAEA) and the Association of Imaging Producers and Equipment Suppliers (AIPES) have been working together to define measures that should be taken to secure the ^{99}Mo supply in the short, medium and long term. A workshop on 'Security of Supply of Medical Isotopes' has been hosted by the NEA in Paris (January 2009). Workshop participants identified measures to enhance the short-term supply security:

- Reactor owners and operators should continue to share information and to enhance coordination of reactor maintenance schedules, with a view to ensuring an uninterrupted global supply of medical isotopes;
- Options for increasing production from existing reactors in times of global shortage should be further explored and encouraged;
- Current economic conditions for irradiation services should be reviewed to provide better incentives to reactor operators, including where the main mission is research in support of national nuclear energy or scientific programmes;
- Unnecessary impediments to the distribution of medical isotopes, such as restrictions in transport capabilities and denial of shipment by airline companies, should be removed;
- Anticipative actions to avoid the dilemma between meeting nuclear safety requirements and meeting health care needs should be encouraged;
- Radiopharmacies, hospitals, health product regulators and the medical community should explore options for more efficient patient scheduling and utilization of ^{99}Mo/^{99m}Tc generators to make best use of currently available supplies of ^{99}Mo and/or other potential alternatives.

The need for a 'High Level Group' on the Security of Supply of Medical Isotopes (HLG-MR) was also recommended to coordinate the efforts [4].

6.1. High Level Group on the Security of Supply of Medical Isotopes

The HLG-MR was created in April 2009 to oversee and assist, where necessary, efforts of the international community to address the challenges of medical isotope supply reliability. The HLG-MR is comprised of 20 experts who are representatives from the governments of Australia, Belgium, Canada, France, Germany, Italy, Japan, Republic of Korea, Netherlands, South Africa and the US, as well as from the European Commission and the International Atomic Energy Agency (IAEA). A first meeting was held in Toronto (June 2009) and a second one in Paris (December 2009). Regulators and delegates from the medical isotope industry and the nuclear medicine community (SNM, EANM) also took part at the discussions.

6.2. Warsaw meeting organized by the IAEA and IAE POLATOM

The IAEA and the Institute of Atomic Energy IAE POLATOM organized a meeting in Warsaw (Poland, September 2009) on 'Assessment of Options for Enhancing ^{99}Mo Production and Availability' [5]. Some 35 international experts, representatives of several companies in the ^{99}Mo supply chain, and concerned government officials participated. The meeting highlighted that several projects in the world could increase the availability of ^{99}Mo on the market at short, mid and long term:

- The new OPAL reactor (Lucas Heights, Australia) currently only supplies domestic ^{99}Mo needs by the irradiation of low enriched uranium (LEU) targets. ANSTO is actively working on a project to supply the US with ^{99}Mo in the near future.

- The US is looking at the possibility to irradiate NRU targets in existing reactors such as MURR (University of Missouri, US) or HFIR (Oak Ridge, US), and to reprocess them in Chalk River (Canada) for ^{99}Mo recovery. Transport issues are to be investigated.
- The research reactor MURR (US) has also another project to irradiate and process LEU targets for the production of ^{99}Mo from 2013. The goal of the project is to supply 30% to 50% of the US domestic ^{99}Mo needs.
- POLATOM (Świerk, Poland) is already manufacturing ^{99}Mo/^{99m}Tc generators with bulk ^{99}Mo supplied by NTP (South Africa) but is also considering a project to irradiate and process LEU targets for the production of ^{99}Mo on its site.
- According to feasibility studies, the FRM-II (Munich, Germany) and the LVR-15 (Rez, Czech Republic) reactors should be able to irradiate HEU targets for the production of ^{99}Mo from 2013 and 2010 respectively. The irradiated targets would be shipped to IRE (Belgium) for reprocessing and ^{99}Mo recovery. Transport issues are to be investigated.
- COVIDIEN is working together with Babcock & Wilcox on a long term project to develop a 200 kW Aqueous Homogeneous Reactor fueled with LEU in solution for ^{99}Mo production.
- The IAEA initiated in 2005 a Coordinated Research Project (CRP) on Developing Techniques for Small-Scale Indigenous Production of ^{99}Mo using LEU or Neutron Activation. The countries involved in the project are Chile, Egypt, Kazakhstan, Libya, Pakistan, Romania, Argentina, Republic of Korea, India, Poland and the US.
- The IAEA initiated also two projects to identify new potential ^{99}Mo producers in the supply chain. Two coalitions have been established: the EARRC (EURASIA Research Reactor Coalition) and the EERRI (East European Research Reactor Initiative).
    - The EARRC Isotopes Coalition is a consortium of existing research reactors, isotope production facilities and market specialists that can make an important contribution to the shortage of ^{99}Mo; the coalition will use the activation route ^{98}Mo(n,**(**)^{99}Mo with natural and/or enriched ^{98}Mo as target material. The countries involved in the project are Kazakhstan, Uzbekistan, Ukraine, Czech Republic, Hungary, Canada and the US.
    - The EERRI initiative has been established in 2008 in line with IAEA efforts to improve research reactors utilization through coalitions and networks. The production of ^{99}Mo in existing facilities is under consideration. The countries involved in the project are Czech Republic, Hungary, Poland and Romania.

6.3. Alternative ^{99}Mo production methods

Several institutions are investigating the possibility of new alternative reactor and accelerator sources to produce ^{99}Mo without the use of HEU or LEU targets in the long term [6].

- The neutron capture process in nuclear reactors by neutron irradiation of natural or enriched ^{98}Mo (24.1% natural abundance) targets by the reaction ^{98}Mo(n,**(**)^{99}Mo.
- The photoneutron process uses a high-powered electron accelerator to irradiate a high-Z converter target such as mercury or tungsten. High-energy photons known as "bremsstrahlung radiation" are produced by the electron beam as it interacts and loses energy in the converter target. The photons can then be used to irradiate another target material placed just behind the convertor, in this case ^{100}Mo (9.6% natural abundance) to produce ^{99}Mo by the reaction ^{100}Mo(**(**,n)^{99}Mo.
- The photofission process is similar to the photoneutron process but involves the fission of natural uranium which produces fission products as ^{99}Mo by the reaction ^{238}U(n,f)^{99}Mo.

The technical feasibility and the commercial viability of these projects should be demonstrated. It is already known that the neutron capture process ^{98}Mo(n,**(**)^{99}Mo is characterized by low production yields and is only appropriate for local needs. The other two processes need to be evaluated theoretically and experimentally.

7. Conclusions

From the different ^{99}Mo shortages which occurred over recent years, several lessons were learned as:

- Need for an optimal communication between the main actors in the ^{99}Mo supply chain and the final users to foresee the difficult periods and try to minimize the impact of a shortage;
- Need for an optimal use of the existing reactor irradiation capacities worldwide through a coordination by the 'Reactor and Isotopes' Working Group of the Association of Imaging Producers and Equipment Suppliers (AIPES);
- Need for the development of short and mid term backup production capacity, including irradiation services and targets processing; security of supply requires overcapacity;
- Need for the development of new long term diversified production capacity, including new technologies if technically and economically appropriate;
- Need for more efficient scheduling and ordering ^{99m}Tc procedures to maximize the number of doses available to the greatest number of patients;
- Need for an optimal coordination of the international efforts by the 'High Level Group' on the Security of Supply of Medical Isotopes (HLG-MR) and especially in the establishment of a financial support policy for existing and new facilities involved in the supply chain.

For the short term, a positive sign came already with the announcement on 17th February 2010 of a collaboration between COVIDIEN and IAE POLATOM to bring the MARIA reactor in the global ^{99}Mo supply chain: irradiation of HEU targets in the MARIA reactor and shipment of the irradiated targets to Petten (Netherlands) for processing and ^{99}Mo separation. This limited contribution could represent about 3% of the global ^{99}Mo needs (to be confirmed) and will help the supply chain. Two similar projects are under consideration: HEU targets irradiations in the LVR-15 (Czech Republic) and FRM-II (Germany) reactors for processing by IRE (Belgium) from 2010 and 2013 respectively. Nevertheless, important structural changes to the ^{99}Mo world supply still need to happen to secure the ^{99}Mo availability in the mid and long term.

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European Nuclear Society

Rue Belliard 65, 1040 Brussels, Belgium
Telephone +32 2 505 30 54, Fax + 32 2 502 39 02
rrfm2010@euronuclear.org - www.euronuclear.org