UTILIZATION OF THE TRIGA RESEARCH REACTOR OF THE UNIVERSITY OF PAVIA

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ABSTRACT

The Laboratory of Applied Nuclear Energy (LENA),operates the TRIGA nuclear research reactor of the University of Pavia for more that 100 days per year, carrying out multidisciplinary activities in collaboration, or as a provider, with several institutions industries and research centres both at national and international level. This paper will present an overview of LENA's reactor utilization.

1 Introduction

The 15 November 2013 will be the 48th year of operations of the TRIGA MARK II nuclear research reactor installed at the University of Pavia, essential tool for the promotion and development of research and nuclerar culture within the University. The Laboratory of Applied Nuclear Energy (LENA), started in 1963 as an idea of the Departement of Chemistry (Radiochemistry group) and continues opening collaborations with the various departments of the University including the Physics Deparment. The Laboratory operates a TRIGA reactor since its installation.Since then, the facility has been operating with numerous results in the field of applied research, education, international development programs as well as providing services to institutions and enterprises, such as the National Institute of Nuclear Physics (INFN), other Universities, industries and research centres both at national and international level, just to mention some. In order to meet the needs of the above-mentioned activities the reactor is operated about 100 days per year, with a cumulative time of 300-400 hours at full power (250 kW) and about 50 hours at indermediate power levels. Irradiation services and nuclear measurements , both operated under ISO 9001 standard, are also provided on commercial basis both to national and international customers.

2 Overview of the irradiation facilities at LENA laboratory

The main facility at LENA is a 250 kW TRIGA (Training Research and Isotope production General Atomics) Mark II, a pool-type research reactor moderated and cooled by light water. Different irradiation channels both in- and out-core, characterized by different neutron spectra, are used to perform experimental activities. The following irradiation facilities and devices are available:

- IBA Cyclotron (18 MeV proton, 9 MeV deuterons) facility for radioisotope production;
- X-Ray industrial generator (250 kV, 12 mA, 936 Gy/h; 350 kV, 6 mA 1050 Gy/h and Gamma-ray Cobalt source (860 Gy/h) ;

- Radiochemistry laboratory equipped with hot cells and devices for manipulation and analysis of any kind of radionuclides;
- Low-background Gamma spectrometry laboratory;
- Radioprotection instrumentation;
- Electronic devices for experiments and for training.

3. Main Research activities with the Pavia TRIGA Reactor

In the following we present the main research fields in which the Pavia TRIGA reactor is involved both directly and as technical support to these activities.

3.1 Boron Neutron Capture Therapy (BNCT)

Since several years the facility has been involved in applied research for medical applications of neutron irradiation using different techniques of analysis; in particular, Boron Neutron Capture Therapy (BNCT), takes up a substantial share of the reactor operating time. BNCT, is an experimental form of binary radiotherapy based on the neutron capture reaction of boron via the reaction $^{10}B(n,\alpha)^{7}Li$. The BNCT thermal neutron irradiations are carried out in a small chamber housed in the modified thermal column of the reactor and that was used to perform BNCT on the explanted liver of patients affected by multiple metastases. For further details see for example Refs. [1,2,3].

3.2 Reactor Physics and Nuclear Engineering

Currently, LENA offers technical support to research activities in two research projects funded by INFN and performed in cooperation with other Universities (Milano Bicocca, Politecnico di Milano), concerning the reactor physics and nuclear engineering: ARCo (*Analysis of Reactor Core*) and Nuc-Smile (Nuclear Subcritical multiplying complex for lead experiments)[4]. Basically, the research line concerns the key issues concerning the design of new generation nuclear power plants and related fuel cycles for the development of flexible computational methods for determining the core-critical parameters, the distribution of neutron fluxes, the time evolution of nuclear fuel composition (i.e. kinetics of poisons, burn-up, production and transmutation of actinides and fission fragments, isotopes decay). The aim of the two projects is a sound validation of specific computational codes by comparison with direct measurements performed at the TRIGA reactor and sub-critical multiplicative complex SM1 of the University of Pavia. Another scientific collaboration was carried on with ENEA (National agency for new technologies, Energy and sustainable economic development), within the framework on the "*New Nuclear from Fission: international collaboration and development of skills in the nuclear field*". The main goal was the measurements of macroscopic quantities for testing of models, codes and nuclear data in research reactors. The activities carried out using the TRIGA Mark II reactor, provided a validation of a methodology for studying the temporal evolution of the composition of nuclear fuel, against the benchmark simulations carried out with the Monte Carlo codes and direct measurements of macroscopic quantities (e.g. as the assessment of the rates of production and transmutation of transuranic elements (TRU) and fission products (FP) by irradiation of fissile material / fertile in the reactor).
Recently the Politecnico of Milano has also carried out a study on the reproduction of the dynamic behavior of the TRIGA Mark II on the entire operative power range (i.e., 0÷250 kW) using a zero dimensional approach [5]. In this work the coupling between neutronics and thermal-hydraulics in natural circulation has been considered.

3.3 Neutron activation analysis

The LENA runs quality control on the content of sodium and chlorine in batches of ion exchange resins on behalf of companies that are suppliers of the nuclear industry. The analyses are routinely carried out with the method of neutron activation (INAA) and allow the achievement of a relative high instrumental sensitivity with quick-to-manage irradiation time in reactor. The tecnique is used as tools in several reserch & development fields for example as quality test and materials characterization [23], study of industrial processes in siderurgy [24] and others dedicated at the activities described here.

3.4 Environmental analysis

Environmental measurements, radioprotection expertise consultancy and investigations in the field of natural and artificial radioactivity are services provided daily by LENA (see for example Ref. [21]). The services are performed both as nuclear site monitoring and also side by side with national institutions or private companies. The main areas of interest are:

- Waste management including radioactive wastes
- Land reclamation and environmental recovery from Oil & Gas activities
- Agricultural products and foodstuffs
- Certification of Building Materials
- Monitoring of water and leachate in the phosphate industry
- Monitoring of radioactivity in air dust

The LENA laboratory successfully participates annually to intercomparison exercises in a network of international laboratories promoted by IAEA with the aim to strengthen the proficiency and reliability of the partecipant laboratories.

3.5 Electronic devices response to radiation

The CMS group of Pavia (Department of Physics and INFN) started a set of measurements on the front-end electronics used by the muon detector of the CMS (Compact Muon Spectrometer) experiment at CERN [6]. The purpose is to understand the average life and the behavior of the front-end of the detectors subjected to high radiation flux, in particular in view of future upgrades. It is intended to realize both measurements of comparison between magnitudes characterizing the system studied before and after irradiation to derive information on the average life of the device is direct measurements of the cross section associated with transient phenomena generated in the devices for effect of irradiation.

3.6 Geosciences

The research activity in the field of fission tracks dating method (see for example Refs. [7,8]) of the C.N.R Institute of Geo-sciences and Geo-resources (University of Pisa, Italy) is carried on through sample neutron irradiation in the experimental channels of the reactor. With this method it is possible to measure the effect, rather than the product, of radioactive decay. In this case, the radioactive decay is the spontaneous fission of ^{238}U which produces, through its high-energy fission fragments, a damage linear (tracks) in the crystal lattice of the mineral. The age of fission tracks is calculated from the number of tracks per unit area observed on the polished surface of the mineral (density of spontaneous tracks). The same method can be applied to measure the concentration in uranium ore, in which ^{238}U is contained as a trace element, and this is done through a second set of fission tracks that are induced through a thermal neutron irradiation provided by the reactor. The research activities of the Laboratory of Geocronology (University of Pisa - Italy) also regard the age determination of minerals through neutron irradiation, flux measurement and isotopic concentrations (^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar, ^{36}Ar) for mass spectrometry (see for example Refs. [9,10,11,12,13]). Among these we cite the collaboration with Montpellier and Cinese.

3.7 Metrological research

The Pavia Radiochemistry and Spectroscopy Unit of INRIM (National Institute of Metrological Research) deals with the study, development and application of radio-analytical, nuclear and spectroscopic methods of measurements of the amount of substance for intercomparison, certification and applied research in various fields (e.g. human health, environment, energy and materials) (see Refs. [14,15,16,17]). The research activities of INRIM are carried on with the Pavia TRIGA reactor. In particular, a methods of Neutron Activation Analysis for the determination of major and trace elements in different types of matrix was developed. In metrology, the activation procedure is used for the certification of reference materials distributed by institutions such as NIST (National Institute of Standards and Technology, USA), IAEA (International Atomic Energy Agency) and IRMM (Italian Institute for Reference Materials and Measurements). All measurement activities and researches carried out by INRIM include a sample irradiation stage at LENA.

3.8 Radiochemistry

The Radiochemistry Area of the Department of Chemistry of Pavia, carries on different research activities, such as the development and application of neutron activation analysis techniques, both instrumental and destructive. New separation methods for the determination of trace elements in geological, cosmological and environmental matrices are just few examples of the ongoin activities (see for example Refs. [18,19,20]).
Another field is the application of neutron activation analysis to archaeological investigations as for provenance studies by using trace element determination and statistical data treatment (multivariate methods and cluster analysis). Typical investigated materials are: marbles, granites, obsidians, pottery, bronze and coins. Neutron activation analysis is also used for the determination the neutron spectrum in the TRIGA Mark II reactor for dating methods in archaeology and geology. The applied experimental part of the Radiochemistry Course of the Chemistry Degree at the University of Pavia, is carried out at the LENA Laboratory in particular:

- preparation of radio-nuclides
- INAA and laboratory best-practice
- optimization of electronic parameters and calibration of Gamma-ray detectors,
- surface contamination measures (e.g.using smear test),
- LSC measurements and radiochemical separation of ^{99m}Tc from Mo activated using MEK technique.

Results are in terms of about 25 students attending the course and 2 master thesis works per year.

3.9 Radioisotope production

Metastable technetium-99 (^{99m}Tc) is the most important and widely radioactive marker in nuclear medicine. Since 2009 the international scientific community has highlighted the critical problem about possible near-future shortage, asking to find out for different production routes from the common production via nuclear reactors. One of the possibilities is to replace the current reactor-based method with accelerator-based systems. In this context, the LENA Laboratory participates with technical support to the APOTEMA INFN research project, in order to find out alternative accelerator-driven ^{99}Mo/^{99m}Tc production routes, in particular for the radiochemical separation of ^{99m}Tc from Mo activated using MEK technique in collaboration with the Radiochemistry Unit of the Pavia Chemistry Department. The APOTEMA INFN project also involves the INFN sections of Legnaro, Padova, Milano and Ferrara. Beside the above mentioned prject, the LENA also prepares some radionuclides to use them as tracer for research experiences in the field of waste treatment. The main radionuclides produced are ^{134}Cs, ^{110m}Ag, ^{24}Na, ^{60}Co.

3.10 Feaseability study for a neutron diffractometer facility

Recently, a feaseability study by the Pavia Department of Physics on a collimated monochromatic neutron beam (coming from the penetrating channel of the TRIGA reactor) for diffractrometry was performed. The simulations were performed by means of MCNP5 in order to test the different elements necessary to achieve a sufficient neutron flux in the sample position. The best configuration (neutron guides, materials) allows to obtain a neutron flux of 8×10^5 n/cm^2 s in samples of typical dimensions in powder diffractrometry experiments. For further detail see Ref [22].

4. Education and Training

Nowadays, the nuclear field (industry, government authorities, R&D organizations and educational institutions) has a constant need for specialized, highly trained and motivated workforce for its sustainability. High standards of performance are expected for the workforce employed in this field and their specialization is a key issue in order to grant and maintain efficiency and high safety levels. Universities can offer, with such facilities, training, laboratories and experiences in different degree courses. Thanks to the deep expertise gained in more than 45 years of operation of the reactor and to the academic context in which it is is operated, LENA can offer a wide range of education and training programs covering most of the topics related to the nuclear field: from safety culture and radioprotection to research reactor maintenance and quality assurance. Training courses are held by qualified professionals working at LENA, or by professors from the University of Pavia, or are a part of the educational path from other University or institutions contributing to courses for Nuclear Engineering, Physics Master Degrees and for post-graduated International Masters in the subjects of Reactor Physics, Radiochemistry, Radiation Protection and Nuclear Instrumentation.

In the accademic year 2012/2013 the laboratory has hosted the practical part of the following courses:

- Course of Radiochemistry (University of Pavia) where teaching exercises are expected in the radiochemistry laboratory (an overview of the typical equipment and activities)
- Practical exercises on reactor kinetic for the course on Nuclear Plant in Nuclear Engineering (University of Milan)
- Course of Cellular Radiobiology (University of Pavia) overview on the facility and its utilization
- Experiences and student stages of the Institute for Advanced Study of Pavia (IUSS) within the International Master on Nuclear and Ioninzing Radiation Technologies - NIRT
- Lessons on neutron physics for course organized by the Physics Department for the Radiobiology course.
- Lessons for the Master in Hadrotherapy (organized by CNAO foundation - National Center of Oncological Hadrotherapy) on various topics related to neutron physics and their application.

In the field of education it's also included the Radiation Officer personal preparation of candidates to the "Radiation Protection Advisor" exam at the Ministry of Labour.
Besides the above described activities addressed to university students and professionals, since many years, LENA has been promoting the information about the nuclear field providing guided visits to the reactor facility. This activity is particularly addressed to students from high schools, in order to promote nuclear energy and give adequate information to those that aims to get a higher education in the nuclear field. In fact, promoting a proper skill transfer avoiding possible loosing in the specific competences needed in the nuclear field is a strong commitment for LENA. The average visitor number per year is about 1500 students/year; LENA provided teaching activities for about 600 hours during the past three years.

4. The Pavia TRIGA research reactor within international networks

The IAEA promotes networking, coalitions and regional collaboration to improve the efficient and sustainable utilization of Research Reactors (RRs). The coalition/network concept involves putting in place cooperative arrangements among research reactor operators, user entities and other stakeholders. A strong partnership is formed leading to increased utilization of individual RRs through collective efforts, including improved self sustainability and self-reliability. In this context, the Pavia TRIGA reactor is present in the Mediterranean Research Reactor Network (MRRN) created by the IAEA.
IAEA CRPs (Coordinate Research Programs) are another important aspect in the field of international cooperation and knowledge sharing. LENA in currently involved in the following ongoing projects:

- "Accelerator-based alternatives to Non-HEU Production of Mo-99/Tc-99m": Lena Laboratory, with the Radiochemistry Unit, carries out research activities that rely on the large experience in the technique of separation and purification of isotopes produced by the nuclear research reactor. The main objective of this research project is to investigate efficient and fast methods for separating ^{99m}Tc from the ^{100}Mo target and for recycling the residual highly expensive ^{100}Mo.

- "Improved I&C Maintenance Techniques using the Plant Computer" aiming to enable the replacement of time based calibrations with condition based calibrations for the reduction in personnel radiation exposure (ALARA), improvement in calibration costs, and adding to plant safety and reliability. LENA actively contributes with tests and benchmarks on actual data retrieved by the automatic data acquisition systems supervising the reactor opration.

In mid 2013, LENA hosted a peer review mission, held by IAEA and intenational experts, regarding the Operation and Maintenance Assesement of the reactor (OMARR). That was a pathfinder mission for a small sized RR as LENA's, and resulted very useful as a chance to assess the operation and maintenance processes and share experience and best practices with the other participants. Based on the positive outcomes of the above mentioned mission, LENA is going to receive a IAEA INSARR (Integrated Safety Assessment for Research Reactors) mission aiming to assess the facility under the nuclear safety point of view, with the overall goal to continously imoprove the efficenciency and effectiveness of all processes related to the safety management of the facility.

5. Conclusions

The experience gained through years of activity at the University of Pavia shows that research reactors facilities, with low power as the Pavia TRIGA reactor, need an expertise team (researches and services development previously part of the institution hosting the facility) present before installation and licensing in order to support the new and incoming activities. The owner should be able to deal with the development and coordination of the activity in many scientific fields; for example, in a University centre, with different departments. From the topics presented in this overview, it becomes clear and it is strongly suggested that Education and Training should be one of the driving activity for this kind of installation. Being a part of a national and international networks, it is also foundamental to be updated in terms of operation experiences and new possible utilizations of the reactor facility.

6. References

[1] A. Zonta et al., Extra-corporeal liver BNCT for the treatment of diffuse metastases: What was learned and what is still to be learned, Appl. Radiat. and Isot., (2009), 67: 67-70.

[2] S. Altieri et al., Neutron autoradiography imaging of selective boron uptake in human metastatic tumours, Appl Rad Isot 66:1850-5 (2008).

[3] Simonetta Geninatti-Crich et al., Magnetic Resonance Imaging guided Neutron Capture Therapy by a dual Gd/B agent targeted to tumor cells via upregulated LDL transporters" CHEMISTRY-A EUROPEAN JOURNAL, 17(30), 8479–8486 (2011).

[4] D. Alloni et al. *Neutron flux characterization of the SM1 sub-critical multiplying complex of the Pavia University*, Progress in Nuclear Energy, 67 (2013) 98-103.

[5] A. Cammi et al., "A zero dimensional model for simulation of TRIGA Mark II dynamic response". Progress in Nuclear Energy Volume 68, September 2013, Pages 43–54

[6] M. Abbrescia et al., Neutron-induced Single Event Upset on the RPC front-end chips for the CMS experiment, Nuclear Instruments and Methods in Physics Research A, 484 (2002) 494–502.

[7] Olivetti V. et al., (2013). Tectonic and climatic signals from apatite detrital fission-track analysis of the Cape Robert Project core records, south Victoria Land, Antarctica. Tectonophysics, 594, 80–90.

[8] Balestrieri M.L. et al, Detrital fission-track-compositional signature of an orogenic chain-hinterland basin system: The case of the late Neogene Quaternary Valdelsa basin (Northern Apennines, Italy). Sedimentary Geology, 289, 159–168.

[9] Di Vincenzo G., Palmeri R. (2001). An ^{40}Ar–^{39}Ar investigation of high-pressure metamorphism and the retrogressive history of mafic eclogites from the Lanterman Range (Antarctica): evidence against a simple temperature control on argon transport in amphibole. Contributions to Mineralogy and Petrology, 141, 15–35.

[10] Di Vincenzo G., Ghiribelli B., Giorgetti G., Palmeri R. (2001) Evidence of a close link between petrology and isotope records: constraints from SEM, EMP, TEM and in situ ^{40}Ar–^{39}Ar laser analyses on multiple generations of white micas (Lanterman Range, Antarctica). Earth and Planetary Science Letters, 192, 389–405.

[11] Di Vincenzo G., Viti C., Rocchi R. (2003). The effect of chlorite interlayering on ^{40}Ar–^{39}Ar biotite dating: an ^{40}Ar–^{39}Ar laserprobe and TEM investigation of variably chloritised biotites. Contributions to Mineralogy and Petrology, 145, 643–658.

[12] M.A. Laurenzi, M.L. Balestrieri, G. Bigazzi, J.C. Hadler Neto, P.J. Iunes, P. Norelli, M. Oddone, A.M. Osorio Araya, J.G. Viramonte (2007) – New constraints on ages of glasses proposed as reference materials for Fission-Track dating. Geostandards and Geoanalytical Research, 31, 105-124.

[13] G. Bigazzi, M.A. Laurenzi, M. Soligo, P. Tuccimei (2008) - Multi-method approach to dating glass: the case of Basiluzzo Islet (Aeolian archipelago, Italy). Journal of Volcanology and Geothermal Research, 177, 244-250.

[14] L.Bergamaschi, E.Rizzio, A.Profumo, M.Gallorini, Determination of trace elements by INAA in urban air particulate matter and transplanted liches, J. Radioanal. Nucl. Chem., Vol. 263, N.3 (2005) 745-750

[15] L.Giordani, E.Rizzio, A.Brandone, Neutron activation analysis in forensic investigations: trace elements characterization of cigarettes, J. Radioanal. Nucl. Chem., Vol. 263, N.3 (2005) 739-744

[16] G.D'Agostino, L.Bergamaschi, L.Giordani, G.Mana, M.Oddone, Instrumental neutron activation analysis of an enriched ^{28}Si single-crystal, Journal of Radioanalytical and Nuclear Chemistry, accepted (25.07.13)

[17] G.D'Agostino, L.Bergamaschi, L.Giordani, G.Mana, E.Massa, M.Oddone, Elemental characterization of the Avogadro silicon crystal WASO 04 by neutron activation analysis, Metrologia 49 (2012) 696–701

[18] G. Bigazzi, M. Oddone, G. Radi "The Italian obsidian sources". Archeometriai Műhely 1(2005)1-12.

[19] M. Botto, A. Deriu, D. Negri, M. Oddone, R. Segnan, G. Trojsi "Caratterizzazione di anfore fenicie e puniche mediante analisi archeometriche" MEDITERRANEA Quaderni annuali dell'Istituto di Studi sulle Civiltà italiche e del Mediterraneo antico, 2(2005)28-56. Pisa 2006.

[20] A. Arias, M. Oddone, G. Bigazzi, A. Di Muro, C. Principe, P. Norelli "New data for the characterisation of Milos obsidians" J. Radioanal. and Nucl. Chem. 268(2006)371-386.

[21] S.Manera, A.Salvini, M.Oddone, L.Strada: "Japanese Green Tea - radioactivity measurments, radiochemical extraction yield determination and some radioprotection considerations". NRC8 - International Conference on Nuclear and Radiochemistry - Session 13 - radioactive elements in the environmental Como Sept. 2012 (submitted to Journal of Life Sciences and Biotechnology (ISSN 2155-8019)).

[22] Reversi L., Studio computazionale per la realizzazione di un fascio di diffrattometria neutronica presso il reattore TRIGA di Pavia. MSc Thesis (2012), University of Pavia.

[23] M. Clemenza, A. Borio di Tigliole, E. Previtali, A. Salvini, "Ultra Sensitive Neutron Activation Measurements of 232Th in Copper", Topical Workshop on Low Radioactivity Techniques - LRT 2010, *AIP Conference Proceedings 1338, 37-43 (2011)*; doi: 10.1063/1.3579557; 2011 American Institute of Physics; ISBN 978-0-7354-0892-0.

[24] B Grassi, G M La Vecchia, S Manera, A Salvini and A Zenoni "Determination of trace elements in metallic materials by neutron activation analysis" (Journal of Physics: Conference Series 41 (2006) p.288-295).