70 years of nuclear energetics

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The first nuclear power plant of the world was connected to the electric grid almost 70 years ago in Obninsk, Russia. Since than more than 600 nuclear power plant units were put into operation worldwide, of which approximately 400 units are still in operation. Additional ~60 units are currently under construction.

The lecture overviews significant milestones of the history of nuclear power generation. Tendencies, statistics will be presented about overall trends of nuclear energetics which reveal underlying reasons. Notable timely and geographical differences will be presented and different and timely changing judgement of countries are discussed.

Looking into the future some lessons learned from the past are examined. The role of nuclear energy in sustainable, safe and economic energy systems are discussed. The rapidly increasing renewable energy sources cause significant changes in the hybrid energy systems which affect the nuclear energy as well. Few recent observations with still open questions for the future will be raised.

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Source-Activity Measurement with Scintillation Crystal Based Detectors under Field Conditions*

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A research and test campaign was carried out on Radio-Isotope Identification Detectors (RIID) by the Detector Testing Laboratory of the Centre for Energy Research in the frame of a Coordinated Research Project (CRP J02012) supported by the International Atomic Energy Agency. The scintillation crystal based RIIDs and other identification detectors are widely used in nuclear security purposes, because, by pushing a button, the source is automatically identified, i.e. they provide quality information. However, their capabilities are not fully exploited (mainly for LaBr3), as the quantitative information of the source (source-activity) could also be extracted from them, which is important due to evaluation of declared commodity information or found illegal cargo, transport, physical protection and the classification of the laboratory. The manufacturers' spectrum evaluation algorithms are capable, but not infallible, and the appearance of the artificial intelligence will represent a big step forward in reliability in the future. This application is technically feasible, but contains many assumptions, pitfalls, questions and uncertainties both on the part of manufacturers and users.

The aim was to investigate the possibility of activity estimation of unknown radiation sources under field conditions and support development with methods, algorithms and specifications. On the one hand, the results of the project are recommendations for laboratories, through illustration and solution of problems: How to start on the way to conform a new measurement method to ISO 17025 standard, that serves as a quality management system. Emphasizing that the correct evaluation and remark of the uncertainty of the measured value is as important as the measured value. On the other hand, there are recommendations for manufacturers: How to start on the way to conform a new detector application to expectations of customers and experts. Emphasizing that, according to the current state of technology, verifiability and supervisionalibility of the spectrum evaluation is necessary, because the competent human/expert and experience can significantly improve the reliability and capability of the measurement.

The typical case of real field condition can be a radioactive source found in a closed barrel or container, as material out of regulatory control, which represents many difficulties in contrast with laboratory conditions. To investigate this, measurements with calibrated sources related to laboratory and modelled field conditions, and analysis of handheld RIID spectra were carried out. Our self-developed, responsive web software (https://csalotzky.github.io/barrel-heatmap/), which handles the calculation, depiction and analysis was used to help the investigation of the source-activity measurement method through more easy, specially designed experimental setup. We strived for the theoretical formulas, practical implementation and measurements to be as simple as possible and at the same time metrologically correct.

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Development of an Electron LINAC Based Photoneutron Reference Field for Metrology-Grade Irradiations*

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In the field of applied nuclear physics, electron linear accelerator (LINAC)-based neutron sources have emerged as versatile tools for various nuclear science applications. This paper presents our innovative efforts to develop an accurately characterized accelerator-driven photoneutron reference field tailored for metrology-grade irradiations.

The setup is based on a Varian Truebeam® medical LINAC, which generates a pulsed electrons beam up to an energy of 22 MeV with a duration about 3 µs. *Bremsstrahlung* photons created by the primary electrons on different target materials further generate photoneutrons through photo-nuclear reactions. The energy distributions of photoneutrons are covering a wide range depending on the material used for the target. To optimize the LINAC for our specific needs, we implemented important modifications aimed at fine-tuning the electron beam. These includes bypassing the internal electron-photon conversion target and removing traditional photon beam filter to preserve beam focus. Relocating the LINAC's monitoring chamber was necessary to avoid its premature ageing from the high intensity focused electron beam. To compensate for the loss of real-time beam data, we developed an alternative methodology using radiochromic films for absorbed dose measurements, enabling deduction of the electron source current. Additionally, accurate control of beam intensity was achieved through adjustments of the electron gun extraction voltage.

The so obtained accelerator-driven neutron sources were accurately characterized in terms of energy and angle distributions. Photoneutron spectra have been measured using a specially developed detection set-up based on a BC-501-A liquid organic scintillator. Data acquisition was synchronized with the accelerator pulses and well-known pulse shape discrimination methods have been used to separate the particles in the total mixed photon-neutron field detected. Unfolding algorithms such as GRAVEL and ML-EM were further used to obtain photoneutron spectra from the recoil protons signal. An assessment of photoneutrons angular distributions with a neutron Beam Loss Monitor system (nBLM) [1] based on a MicroMegas detector was also performed.

Leveraging these experimental findings, we developed a detailed model of the experimental setup, allowing accurate Monte-Carlo simulations of various irradiation configurations. The implications of our work extend beyond dosimetry and metrology, offering viable alternatives for advancements in Boron Neutron Capture Therapy (BNCT) [2], materials science through neutron activation analysis [3], nuclear instrumentation characterization in a well-controlled mixed n/γ field, and applications related to nuclear reactors [4]. Researchers and practitioners can count on a reference field to calibrate instruments, validate simulations, and conduct experiments with an increased level of confidence and accuracy.

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Antineutrino detection concepts for safeguards at spent nuclear fuel facilities*

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Nuclear fuel – during reactor operation and after discharge of the fuel – requires safeguards to ensure non-proliferation of fissile material. Current safeguarding approaches for spent nuclear fuel (SNF) in spent fuel storage facilities (SFSFs), whether interim storage or final disposal, utilize a combination of material accountancy, containment and surveillance, and design information verification. Part of these safeguards techniques are detectors used to verify the continuity of knowledge and hence, the validity of safeguards declarations. A new approach to safeguards is the measurement of antineutrino emissions from the ongoing beta decay of fission fragments to provide additional complementary information on the potential diversion of nuclear material or to assist in re-verification scenarios as antineutrinos penetrate any shielding, structure, or geology effectively unhindered and harmlessly.

Antineutrino-based safeguards and related applications [1] have been discussed and have been under development for reactor facilities for several years, with several approaches being actively pursued ranging from scintillator-based technologies to large water Cherenkov detectors, each tailored to the respective deployment scenarios. Extending this approach to SNF presents unique challenges as the antineutrino flux of cooling fuel elements is several orders of magnitudes lower than during reactor operation. In addition, the antineutrino spectrum from SNF is softer, requiring higher sensitivity close to the inverse beta decay energy threshold. This work studies and compares previously proposed reactor monitoring technologies with a novel detection concept using a liquid-organic (LOr) time projection chamber (TPC) [2,3]. The LOr-TPC concept combines the advantages of TPCs with the required target hydrogen atoms of organic media like organic scintillators.

The expected signal and background rate, sensitivity to inventory changes, and directional capabilities for signal localisation and background rejection are compared for several benchmark technologies. This comparison will investigate two simplified storage sites with varying fuel cooling times and detector deployment scenarios. This comparison will be used to understand the feasibility of current and upcoming detector technology as applied safeguards tool and establish detector performance requirements for providing complementary safeguards for SNF storage facilities.

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Novel Method for Computing Full-Energy Peak Efficiency of Gamma Spectrometry Systems Using Hybrid Integral Expression and Monte Carlo Simulation

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Computed values of the full-energy peak (FEP) efficiency play a crucial role in gamma spectrometry measurements for assessing the activity of gamma-emitting radionuclides due to the limitations of the relative method of measurement. This paper explores various methods for computing the FEP efficiency, including Monte Carlo (MC) simulation, deterministic methods based on integral expressions, and hybrid approaches that combine both techniques. The MC simulation method, widely considered the gold standard, involves simulating photon transport to calculate the FEP efficiency, requiring prior calibration of the detector's geometric model. Deterministic methods leverage integral expressions utilizing probability functions to derive exact and universal FEP efficiency expressions for point and volume sources.

In this study, a novel method is proposed that integrates the integral equation with MC simulation to compute the FEP efficiency of coaxial HPGe detectors for cylindrical sources emitting photons in the 60-2000 keV range. The method focuses on homogeneous cylindrical sources with uniform activity distribution placed coaxially with the detector axis within a defined spatial boundary. By employing a grid-based interpolation technique to determine detector responses and MC integration for computing attenuation factors, the FEP efficiency of cylindrical samples is computed using numerical integration based on the midpoint rule. This innovative approach offers a robust and efficient way to calculate the FEP efficiency for gamma spectrometry systems, enhancing the accuracy and reliability of activity measurements in nuclear applications.

Keywords: gamma-ray spectrometry, deterministic methods, Monte Carlo simulation, numerical integration