REPORT ON ESARDA NOVEL APPROACHES / NOVEL TECHNOLOGIES WORKING GROUP (NA/NT WG)

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Vice Chair: Antonin Vacheret, Oxford University
Secretary: Mika Nikkinen, CTBTO

Summary

The ESARDA Novel Approaches and Novel Technologies (NA/NT) annual workshop was held at Oxford University, UK on 27-28 March 2014. Over 40 experts participated in the meeting to address workshop topics covering, inter alia, anti-neutrino detection systems, new neutron detectors, safeguards R&D programmes, non-proliferation, treaty verification, arms control verification technologies and advances in simulations, nuclear data and novel measurement methods. Highlights, of this meeting are collected in this document.
1 Introduction

The ESARDA working group for NA/NT has identified several emerging technologies with potential use for safeguards. Often their technological readiness level is low and considerable R&D is required before they are mature enough for inspection use. Recently, the working group, considered three scientific areas or applications in more detail: optics, antineutrinos and arms control verification technologies (ACVT). The latter two formed the skeleton of the NA/NT meeting agenda in Oxford keeping the focus more towards neutron detection technologies.

Antineutrino measurements have a close link to the development of new types of neutron detectors, which are also the key technology in nuclear security. Therefore, regardless the application, it was natural to arrange a joint meeting with scientists working with neutron detection. It is envisaged that both groups will benefit from the understanding of the technological development in a broader scale.

The workshop discussed several items of interest to non-proliferation, treaty verification and arms control. A special satellite meeting was arranged on 26th March 2014 on ACVT. The outcome of this meeting is reported separately.

Presently, and also in the future, NA/NT will aim at providing expert advice and assistance to international nuclear inspectorates on novel approaches and technologies which have the potential to improve safeguards and nuclear security. Technical methods to verify international treaties, present or future, involving nuclear disarmament, arms control and non-proliferation are an important field of work.

Besides nuclear sciences, NA/NT often refers to other disciplines. The aim is to promote scientific research and development on methods and techniques for safeguards and nuclear security. Scientific meetings, such as the one in Oxford University, are important for information sharing and understanding the progress in the development of different detection technologies. The meeting in Oxford provided invaluable contacts and feedback to carry on scientific work towards various in-field applications.

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2 Presentations

The following review of the lectures is from the perception of the Chair, Vice Chair and the Secretary. The notes are ordered session by session. More precise information on the context is given by the authors in the abstracts and presentations, which are available in CIRCABC web page of ESARDA NA/NT (https://circabc.europa.eu), or directly, from the Secretary.

2.1 Neutron Detection Technologies

Neutron detection technologies focus on the replacement of widely used $^3$He filled detectors with gas, liquid or solid detector alternatives. Several detector types were discussed to a various degree of detail, including a Nordic comparison study on their capabilities. In order to find practical applications in nuclear safety, security and safeguards, new detectors need to match $^3$He-based detectors in terms of operation and performance.

Several neutron detectors are designed to use inorganic crystals loaded with nuclides having a large cross-section for neutron capture. In general, they require a moderator, e.g. polyethylene, in order to thermalize incident neutrons and increase detection efficiency. Alternatively, detection could be based on inelastic scattering of fast neutrons, which results in high-energy photons.

A promising solid neutron detection material is plastic scintillator loaded with either boron or LiZnS. Indirect neutron detection with a NaI spectrometer at high photon energies (3.5 – 8 MeV) has the potential to detect shielded sources of neutrons as it reacts on neutron-induced photons and on photons generated directly in the fission process. It is difficult to shield them both simultaneously.

The $^4$He based detector was discussed in detail. Its operation is based on elastic scattering of incident neutrons and it has a very fast response. Consequently, and unlike the case for $^3$He whose functioning is based on nuclear absorption, there is no need to employ a moderator to thermalize neutrons. The detector offers strong gamma rejection.

In addition, examples of nuclear tomography, i.e. imaging using (mono-energetic) gamma rays and neutron beams were discussed. Efficient calculation methods for detector response, matching Monte Carlo simulations were presented alongside simulations optimising detector shape, collimation and shielding.

2.2 Safeguards R&D programmes

Production of $^{236}$Np and $^{236}$Pu for isotopic dilution mass spectrometry (IDMS) analysis was reported. It was estimated that 1 μg of $^{236}$Np will be available in late 2014, and thereafter NPL will be able to produce 1-10 μg annually. Plutonium-236 production is a straightforward operation. Purity of $^{236}$Pu is good (<0.001% $^{238}$Pu) and it can be made in quantities larger than 100 kBq relatively easily.

The USA's Next Generation Safeguard Initiatives (NGSI) was presented. This is a robust, multi-year DOE/NNSA program to support the policies, concepts, technologies, expertise, and international
infrastructure necessary to strengthen and sustain the international safeguards system as it evolves to meet new challenges. The program has a volume of $41M USD (2013). Focus areas are: measurement technology; containment and surveillance; destructive analysis; standards and testing infrastructure; detector materials; data authentication; data integration; and design information verification (DIV) tools and methods.

The IAEA Technology Foresight project’s approaches and challenges were introduced. This included the implementation plan and the idea to have feedback-driven product development. The vision of building technology awareness envisages a concept for an inspector in 21st century, applying innovations developed for other fields and control over problem solutions, particularly to the extent that the chosen solution does not itself develop into new problem.

2.3 Non-Proliferation, Treaty Verification and Arms Control

Non-proliferation and verification calculations were presented based on a method that uses pure transport theory (Comet). The method was compared with Monte-Carlo calculations resulting in comparable outcomes. However, the major benefit of the Comet method is that it is essentially faster than Monte-Carlo calculations.

A low-dose, active interrogation method is based on $^{11}\text{B}(d,ny)^{12}\text{C}$ reaction (4 MeV deuterons). It produces mono-energetic photons (4.4 MeV and 15.1 MeV) and fast neutrons peaking at 12 MeV. Transmission imaging can detect small amounts of special nuclear material (SNM) and yet the target receives a low dose (< 200 µSv). With this approach, a more compact accelerator design is possible (relocatable device). The multi-particle approach gives both position and isotopic identification of SNM. Cherenkov detectors are under study to improve imaging and to decrease the background. Robot based detector systems are being studied as well. Both experimental development and software development are in progress.

Challenges with Comprehensive Test-Ban Treaty (CTBT) technical verification were highlighted. Technology development is opening new approaches to the treaty verification methodology. Improvement of sampling and detection systems are studied to further develop the radioactive material detection in global scale. Several technical challenges were presented, such as filter-less particle collection, higher resolution detectors and advanced data analysis. The Comprehensive Test-Ban Treaty Organization (CTBTO) has formalized its technology foresight process to follow-up the development.

2.4 Antineutrinos

Progress in this field is fostered by fundamental research in neutrino physics, i.e. the problem of missing solar neutrinos, the question of neutrino mass and oscillations between three known neutrino families, and recently, probing the existence of a sterile neutrino. As a spin-off from those activities the idea of monitoring nuclear reactors emerged. A nuclear reactor core contains large amounts of beta emitters and, therefore, it is an abundant source of anti-neutrinos. In recent years, the development of antineutrino detectors has made considerable progress in terms of increasing efficiency and reducing size.
Detection of (electron) antineutrinos is based on inverse beta decay. The target of this reaction is a proton with a positron and neutron as products, which are detected in coincidence. The positron annihilates, emitting (most often) two gamma photons of a defined energy. The neutron capture is delayed with respect to the gamma emission by a time interval of the order of 100 microseconds. Classical antineutrino detectors contain liquid scintillators doped with gadolinium. Smaller solid-state detectors are being pursued. A remote reactor monitoring concept was introduced, based on a large detector (thousand tons) deployed underground (WATCHMAN).

A segmented antineutrino detector has been designed by Oxford University. The detector is a plastic scintillator loaded with $^6$Li (SoLid). A measurement campaign at SCK-CEN reactor is underway. The construction of the detector system allows for spatial localization of the inverse beta reaction; namely, an estimation of the distance between positron emission and neutron capture. Another example of a plastic scintillator-based system, with interleaved sheets of gadolinium oxide, was presented. The large detector footprint (1.5 tons) enables the detection of the gamma-rays from the capture of neutron on gadolinium. This system was directly leveraged from the development of a neutrino science experiment called T2K, which allows measurement of the incident radiation energy. Plans have been made to deploy and test this system at the Wylfa power station (UK), using a standard cargo container.

The advantage of antineutrino-based measurement technology in safeguards stems from its non-intrusiveness and difficulties (for the inspected party) to provide shielding of the emitted antineutrinos. This technology has a potential of being used for reactor monitoring, particularly for those types of reactor which do not have itemized cores (e.g. pebble bed, liquid core). Theoretical studies of detector response revealed a difference between the neutrino spectrum from $^{239}$Pu and $^{235}$U, providing the possibility to verify fuel burn-up, non-declared reactor re-fuelling, or production of fissile material. The challenge resides in ensuring high background noise rejection.

A different approach to measure antineutrinos was presented. It was postulated that antineutrinos may have an influence on $\beta^+$ decay ($^{22}$Na). A field test showed some preliminary support to the hypothesis. However, the results are still under investigation to look at possible instrumental effects related to the data acquired.

### 2.5 Simulations, Nuclear Data and Novel Measurement Methods

A combination of shielding and collimation can improve the sensitivity of portal monitors to detect radiological and nuclear materials hidden in vehicles. Optimization studies performed using Monte Carlo simulations of ‘model’ systems indicate that additional attenuation in front of the detector can improve detection capability (collimator 5-10 cm).

The IAEA’s Nuclear Data Section (NDS) (https://www-nds.iaea.org/) supports and develops experimental and evaluated databases for general use and also for safeguards. The NDS has completed and corrected missed data on neutron multiplicities that were not included in EXFOR\(^2\) and also follows-up the developments in nuclear resonance fluorescence (NFR).

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\(^2\) EXFOR is a database of experimental reaction data
Available antineutrino measurements were overviewed. It was found that main reactor isotopes \( ^{235,238}\text{U}, ^{239,241}\text{Pu} \) were measured at only two facilities. Currently the NDS runs an IAEA Coordinated Research Project (CRP), “Database for Beta-Delayed Neutron Emission Data”, in which several antineutrino experts are involved.

Conversion electron spectra, provided by the ENSDF database, have been checked against data recently published by K. Peräjärvi et al. (Radioanal. Nucl. Chem. 299(2014)229). This comparison showed that measured data and Evaluated Nuclear Structure Data File (ENSDF) data differ essentially, whereas other library data (http://bricc.anu.edu.au/) are in better harmony with the measurements.

List mode data acquisition is the future of radioactivity and other measurements. The European Reference Network for Critical Infrastructure Protection (ERNCIP) has made an initiative to develop a standard for list-mode data acquisition. This helps to interface various data analysis tools. Presentation on list-mode data acquisition to the IEC/TC 45 WG 9 committee was given in June 2013. The response from the committee was positive, and the next step is to prepare a new work item proposal. The next IEC/TC 45 WG 9 meeting, where the ERNCIP RN TG should introduce the list-mode work item proposal, is scheduled for October 2014.

A list-mode data acquisition hardware and software system has been developed in Hungary to be used for neutron coincidence and multiplicity measurements. A training system (virtual source) for replaying pulse trains registered in list mode has also been developed. It is an excellent educational tool that avoids the radiation exposure of the trainee.

ENEA\(^3\) presented their progress in implementing tools to identify radioactive materials. They can be used for secondary measurement of suspected material found in border control.

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\(^3\)ENEA is the name of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development.
3 General Discussion

Julian Whichello, IAEA, reminded meeting participants that NA/NT WG was established in Jan 2010, during the IAEA’s development of a long-term strategy, which aimed at guiding its future R&D development for 2012-2023. To achieve its long-term strategic objectives, the IAEA identified R&D needs in the following general areas:

- Concepts and approaches;
- Detection of undeclared nuclear material and activities;
- Safeguards equipment and communication;
- Information technology, collection, analysis and security;
- Analytical services;
- New mandates; and
- Training

Of particular importance were *inter alia*: the further expansion of remote monitoring and use of operators’ monitoring systems; enhanced communication between IAEA offices, inspectors in the field and States Parties; early detection of clandestine activities (e.g. HEU production); and if called upon, possible future treaty verification mandates (e.g. naval propulsion, FMCT, and weapons dismantlement verification).

To provide the expertise and support that will be necessary to meet the Agency's R&D needs, outreach should be broadened to create further links to universities, national laboratories and industry. Such outreach will necessitate acquainting a new network of experts involved in addressing specific monitoring and verification needs, including an understanding of the nuclear fuel cycle, and its associated indicators (process input materials) and the signatures (process output materials) at the level appropriate to develop solutions for safeguards. The NA/NT WG is a valuable resource in these endeavors, providing a constructive forum for the exchange of ideas and resources to undertake and advise on technologies.

Antonin Vacheret, Oxford University, pointed out that the NA/NT domain is an interesting mix of technologies. The novel technologies working group should keep its focus on radiation detectors and the need of the field but should take into account the increasing integration of various technologies that is currently changing the way we approach new problems. R&D is increasingly a cross-disciplinary field. Fostering less mature and more risky technologies, especially those looking at achieving substantial increase in sensitivity like antineutrino detection, is also key to promote current boundaries. As it has been shown during the workshop, the antineutrino sub-working group has been very active recently and detection limits are improving. Because antineutrino detectors have to be first very efficient neutron detectors, this research has also a more direct, albeit less predictable, impact on neutron detection techniques.

Mika Nikkinen, CTBTO, agreed that antineutrino R&D has increased technology readiness level but the progress has not yet impressed safeguards inspectorates. There is further need for case studies. Another key area is the development of novel neutron detectors for safety, security and safeguards. Such R&D has a close linkagte to antineutrino research where neutron detection plays the key role.

From the CTBT point of view, three R&D areas are of importance:
1. Better nuclear data (various fission yields and gamma/conversion electron yields)
2. List-mode data acquisition for beta-gamma, gamma-gamma and gamma-optical
3. Optical methods for determination of the amount of Xe and Ar gas in the measurement cell

Dimitri Finker, IAEA, sees the role of NA/NT WG as a truly interactive forum where everyone not only presents new ideas to the other NA/NT participants but also leaves the workshop with fresh ideas coming from cross-disciplinary fields. The IAEA long-term R&D plan is of high importance to help understanding the priorities of IAEA-SG, and highlights that R&D should not provide only new detection and verification methods of undeclared activities but also identify opportunities how to apply technological evolutions to make inspections more efficient.

Hamid Tagziria pointed out the increasing need to develop arms control verification technologies (ACVT). Multiple disciplines are required, such as optical, seals and non-destructive assay (NDA) techniques. Inspection perspective is highly important. Much progress has already happened in identifying possible verification technologies\(^5\). He added that substantial R&D and progress has also been made since the first IAEA meeting on antineutrino detectors for safeguards, which if considered part of safeguards-by-design policy would have better chances for success and acceptance.

Taissa Sobolev, DOE/NNSA, raised the question on how the working group decides which areas are selected for NA/NT and suggested considering a needs-driven approach to ensure that the work reflects the expectations of the inspectorates and end-users of the technology.

Imre Pazcit, Chalmers University of Technology, pointed out that better nuclear data are needed; in particular, for the correlations of neutron energies in fission for various types of reactors. Stanislav Simakov, IAEA, agreed but referred to limited resources of IAEA. Mika Nikkinen responded "why not to have a CRP in IAEA on this topic?"

Harri Toivonen, STUK, reminded the meeting that the NA/NT started its work in trying to identify technologies that are important for safeguards. Such a draft list was made in 2011. This approach was then the basis for the development of a similar list for ACVT. The activity of the NA/NT WG depends much on the Chair, Vice Chair and Secretary. The key question is how to draw the attention of top scientists in different disciplines.