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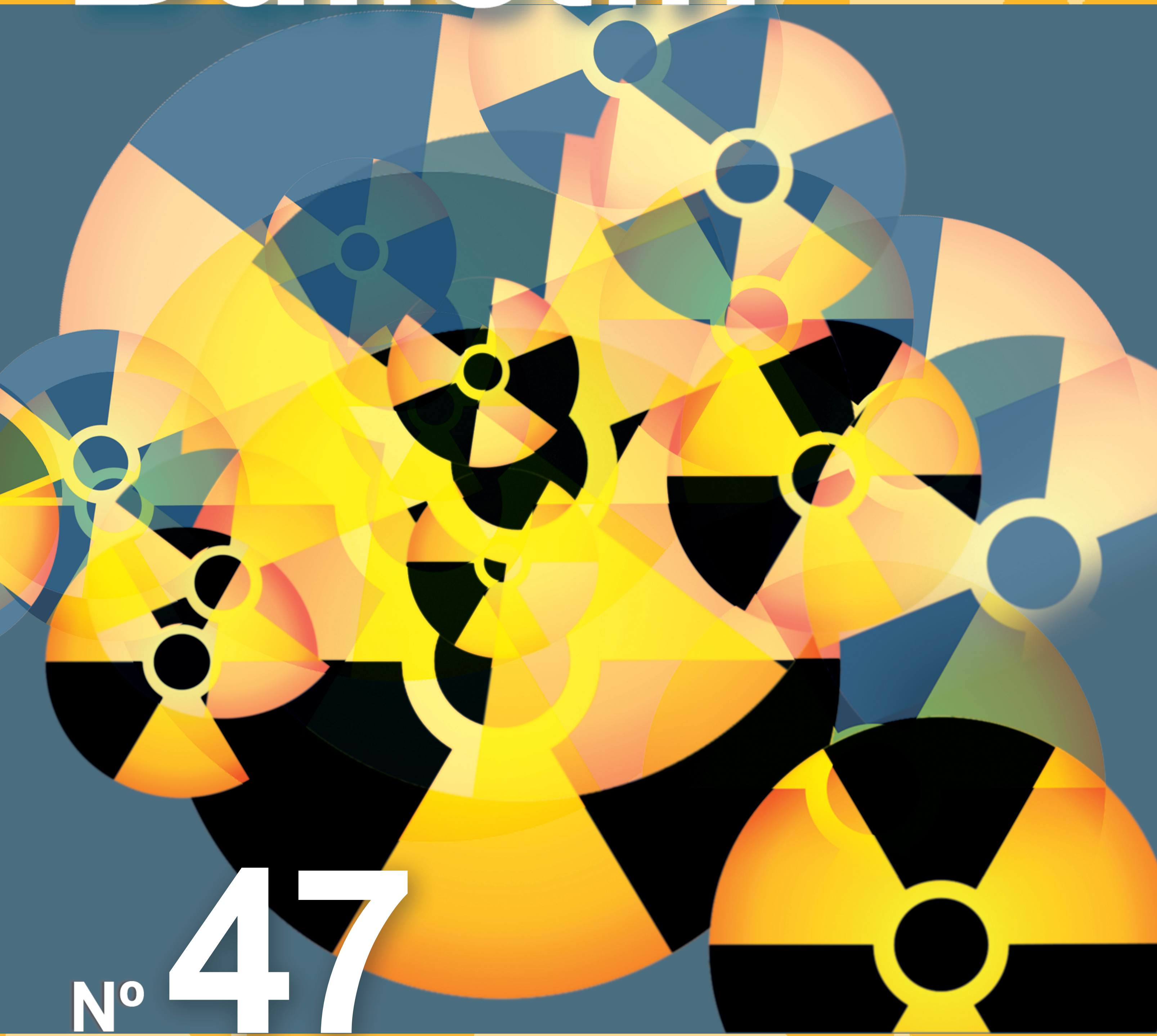

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ESARDA
European Safeguards Research and Development Association

Bulletin

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Letter from the Editor

Dear colleagues,

Either in your hands or on your screen you have the 47th issue of the ESARDA bulletin which in addition to a letter to the editor, a Tribune paper and working group reports as has been customary to do, contains thirteen peer review papers.

This extended peer review section, already seen in issue 46, signals a drive and intent to make the ESARDA bulletin a much improved journal and forum allowing various actors (professionals, scientists and authors generally) to disseminate and publish their work. The papers come from various sources including those judged best in each session of ESARDA symposia and workshops as well as those independently submitted. Peer reviewing, itself is carried out by independent experts in the field including members of the editorial committee where appropriate and is instrumental in improving and guaranteeing the good quality of research in each paper published and maintaining public confidence in it and in the journal by extension (as previously pointed out in the editorial of issue 33). Another new aspect of the bulletin is the widening of the thematic areas covered which go beyond the traditional safeguards applications to reach, for example novel technologies, nuclear security, NDA for nuclear disarmament, NDA for nuclear disarmament, safeguards by design, export control etc. This is also representative of the variety of working groups and activities within ESARDA as recently witnessed during its 34th annual meeting in Luxemburg.

I am pleased to announce that the ESARDA bulletin is being evaluated by REUTERS-THOMSON in view of citation with impact factor based on sustained quality and regularity (bi-annual plus special issues when appropriate). Contributions from authors and the reviewers' assistance are thus most welcome not only as regards to the bulletin but also for papers submitted to forthcoming symposia (the next one to be held in Bruges (Belgium) about the 21 to 24 May 2013). Contributions for issue 48 due to be published in December 2012 are now being sought and submission deadline is set for the end of September. Contributions which do not qualify for peer reviewing may also be published in non peer reviewed sections of the bulletin subject to the editorial committee's approval.

Papers should be submitted to Esarda bulletin@jrc.ec.europa.eu following instructions to authors found in http://esarda2.jrc.it/bulletin and giving the names and e-mail addresses of two potential reviewers who are both experts in the field and independent. The bulletins are downloadable from the above web site and hard copies are posted to more than 1100 institutions, universities, libraries and individuals worldwide, free of charge.

As chairman of the editorial committee and editor of the ESARDA bulletin and on behalf of the editorial committee I would like to thank all authors and reviewers for their current and future contributions to further develop and improve the quality, impact and sustainability of the bulletin.

Finally, I also have pleasure to inform you, on behalf of the initiative taken by the INMM, ESARDA and IAEA, that the NuSaSET Portal and Social Network (www.nusaset.org) has been launched aiming to promote and share knowledge and training in the field of Nuclear Safeguards and Nuclear Security, which indeed goes hand in hand with various training programs being provided and with the scope of this bulletin.

I welcome any suggestion you may have for the bulletin and wish you a successful second half of the year.

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Letter to the Editor

Higher Order Dead Time Corrections for Neutron Multiplicity Counting

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Neutron multiplicity counting using shift-register logic is a standard technique for the quantification of plutonium for the purposes of international nuclear safeguards. For impure materials, where the known-alpha method of traditional neutron coincidence counting is inapplicable, it can significantly improve accuracy. For over two decades the predominant approach to deriving dead time corrected singles, doubles, and triples has been based on the procedure developed by Dytlewski [1] for paralyzable dead time losses. Recently a self-consistent singles dead time correction has been reported to replace the first order ad hoc correction adopted by Dytlewski, and also correction coefficients for quads counting have been given [2]. Here we briefly summarize this refined and expanded Dytlewski scheme and additionally present new results allowing the dead time compensated pents rates to be calculated according to the same Dytlewski dead time model assumptions. All of the expressions are straight forward to apply in practice and involve just a single dead time parameter, d.

We represent the reals plus accidentals and accidentals histograms by N_i and B_i respectively, and chose to work for the purposes of the present illustration in terms of mixed-gate multiplicity shift-register expressions [2,3]. The dead time corrected singles, S, doubles, D, triples, T, quads Q, and pents, P, rates, may then be expressed as follows:

$$S = C_S \cdot \frac{1}{t} \cdot \sum_{i=0}^{\infty} B_i = \left(\frac{1}{T_g} \cdot \frac{\sum_{i=1}^{\infty} \alpha_i B_i}{\sum_{i=0}^{\infty} B_i} \right)$$

$$D = C_S \cdot \frac{1}{t} \cdot \sum_{i=1}^{\infty} \alpha_i \cdot (N_i - B_i)$$

$$T = C_S \cdot \frac{1}{t} \cdot \sum_{i=2}^{\infty} \beta_i \cdot (N_i - B_i) - S \cdot D \cdot T_g$$

$$Q = C_S \cdot \frac{1}{t} \cdot \sum_{i=3}^{\infty} \gamma_i \cdot (N_i - B_i) - \left(\frac{1}{T_g} \frac{\sum_{i=2}^{\infty} \beta_i B_i}{\sum_{i=0}^{\infty} \beta_i} \right) \cdot (D \cdot T_g) - S \cdot (T \cdot T_g)$$

$$P = C_S \cdot \frac{1}{t} \cdot \sum_{i=4}^{\infty} \eta_i \cdot (N_i - B_i) - \left(\frac{1}{T_g} \cdot \frac{\sum_{i=3}^{\infty} \gamma_i B_i}{\sum_{i=0}^{\infty} B_i} \right) \cdot (D \cdot T_g) - \left(\frac{1}{T_g} \cdot \frac{\sum_{i=2}^{\infty} \beta_i B_i}{\sum_{i=0}^{\infty} B_i} \right) \cdot (T \cdot T_g) - S \cdot (Q \cdot T_g)$$

In these expressions is the assay time, T_g is the duration of the coincidence gate, and C_S is the singles rate correction factor given by:

$$C_S = \frac{\sum_{i=1}^{\infty} \alpha_i \cdot B_i}{\sum_{i=1}^{\infty} i \cdot B_i}$$

Here we are assuming that every neutron event recorded by the multiplicity shift-register circuit opens both a reals plus accidentals and an accidentals gate. However, in the case where the accidentals gate is sampled at a clock frequency (for example in the so called fast accidentals sampling scheme) all that is required is a simple normalization of the B_i histogram.

The α_i, β_i, γ_i and η_i functions are defined below in terms of the ratio of the dead time to gate width through the parameter, $\phi = d/T_g$:

$$\alpha_0 = 0$$

$$\alpha_1 = 1$$

and for $n \geq 2$

$$(\alpha_n - 1) = \sum_{k=0}^{n-2} \binom{n-1}{k+1} \frac{(k+1)^k \phi^k}{[1-(k+1)\phi]^{k+2}}$$

$$\beta_0 = \beta_1 = 0$$

$$\beta_2 = \frac{1}{(1-\phi)^2}$$

and for $n \geq 3$

$$\beta_n - (\alpha_n - 1) = \sum_{k=0}^{n-3} \binom{n-1}{k+2} \frac{(k+1)(k+2)^k \phi^k}{[1-(k+2)\phi]^{k+3}}$$

$$\gamma_0 = \gamma_1 = \gamma_2 = 0$$

$$\gamma_3 = \frac{1}{(1-2\phi)^3}$$

and for $n \geq 4$

$$\gamma_n - [\beta_n - (\alpha_n - 1)] = \sum_{k=0}^{n-4} \binom{n-1}{k+3} \frac{\frac{1}{2}(k+1)(k+2)(k+3)^k \phi^k}{[1-(k+3)\phi]^{k+4}}$$

$$\eta_0 = \eta_1 = \eta_2 = \eta_3 = 0$$

$$\eta_4 = \frac{1}{(1-3\phi)^4}$$

and for $n \geq 5$

$$\eta_n - \{\gamma_n - [\beta_n - (\alpha_n - 1)]\} = \sum_{k=0}^{n-5} \binom{n-1}{k+4} \frac{\frac{1}{6}(k+1)(k+2)(k+3)(k+4)^k \phi^k}{[1-(k+4)\phi]^{k+5}}$$

These expressions for C_S and the γ_n functions are recent additions to Dytlewski's original method [2]. The expressions for the η_n functions are being reported here for the first time. We note that extension beyond pents counting is also possible but, because for all cases of routine practical interest in quantitative neutron multiplicity counting for safeguards quads is already at the limit of statistical viability, we have elected to stop at pents for the purposes of this communication. The beauty of Dytlewski's work [1] as extended here is that it provides a prescription for how to calculate higher reduced factorial moments directly from the item specific MSR histograms as simple vector operators. Within the assumptions and limitation of the underlying dead time model the same approach may be applied to the signal triggered interval (STI, reals plus accidentals) histogram, and the random triggered interval (RTI, accidentals or periodic) histogram. Thus in principle these dead time coefficients may be used to extract dead time corrected correlated rates from the STI-only, RTI-only or MIXed STI and RTI expressions given in [3]. The RTI data need not be acquired using a multiplicity shift-register and is essentially Feynman sampling but with overlapping gates.

With these modifications and additions there now exists a clear path, for the first time, to study the potential advantages of incorporating higher order correlated counting rates into the verification and safeguarding of fissioning items using the simplistic yet widely adopted Dytlewski dead time model. A detailed paper discussing the implications of these advances is being readied for publication.

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[3] S. Croft, R.D. McElroy, S. Philips, M.F. Villani and L.G. Evans, Dead Time Behaviors in Passive Neutron Correlation Counting, Waste Management Symposia, WM'07 February 25 – March 1 2007, Tucson, Arizona, USA. Paper 7258.

ESARDA Tribune

Twenty years of ABACC: Accomplishments, lessons learnt and future perspectives

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Abstract:

From the inception of the implementation of the Quadripartite Agreement (INFCIRC/435), in 1991, ABACC has had an important role at the non-proliferation agenda and has also been an active player in the international safeguards. It was necessary for ABACC to develop a technical capacity to face the challenges to be a safeguards agency and to gain credibility in the nuclear safeguards world. This capacity means to develop and implement safeguards systems in the technical area, in the inspection framework, in the conceptual analysis of processes and approaches and in the political scenario. These tasks conducted the strategic plan of ABACC on the last 20 years.

Among the accomplishments, ABACC has been involved in the application of safeguards to sensitive and complex installations, in developing safeguards instrumentation, in establishing a technical and trained inspectorate, in constructing a cooperative and coordinate environment with IAEA for safeguards application. Other challenges as R&D of equipment and quality assurance systems were also managed during all these years.

ESARDA is one forum that ABACC is involved and always shares experience and ideas. On July 18th, 2011 ABACC will formally complete 20 years. This paper summarizes the accomplishments, lessons learnt and future actions for strengthen the ABACC safeguards role. It also addresses the collaboration of ABACC with other organizations in the non-proliferation and international safeguards arena.

Keywords: ABACC, Regional Systems, Safeguards Agency, Quadripartite Agreement.

1. Introduction

Considering the nuclear development of the two countries, not having a comprehensive safeguards agreement in force while willing to demonstrate to the world the peaceful use of their nuclear programs, Argentina and Brazil decided to establish a Common System of Accounting and Control of Nuclear Materials (SCCC) in 1990. This means that the norms for nuclear material control should be similar in the two countries and all nuclear materials and facilities should be subject to the same safeguards requirements. The SCCC was formalized through the Bilateral Agreement (INFCIRC/395), which was signed in July 1991 and ratified by the Congresses of the two countries six months later. To apply the SCCC, the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials -ABACC- was created on July 18th, 1991.

The rules and boundary conditions for the application of the SCCC by the Secretariat of ABACC are designed in the Bilateral Agreement and in one specific document named *General Procedures of the SCCC,* which is approved by representatives from each country, who act as Members of the Commission of ABACC.

The safeguards measures foreseen in the SCCC refer to all declared nuclear material after a defined starting point, although the existence of undeclared nuclear material and facilities is not excluded (i.e. facility misuse is considered). In the SCCC there are no provisions to apply safeguards either to non-nuclear materials or to research and development activities not involving the processing or storage of nuclear materials. The safeguards measures establish by the SCCC complied with the comprehensive type of agreements like the INFCIRC 153.

Also in December 1991 Argentina, Brazil, ABACC and IAEA signed the Quadripartite Agreement which entered into force In March 1994. Through this comprehensive safeguards agreement the countries submit all nuclear materials in all nuclear activities to the IAEA safeguards. Under this agreement, the IAEA, in carrying out its verification activities, shall make full use of the SCCC. Furthermore, the IAEA and ABACC shall draw independent conclusions, but must avoid unnecessary duplication of ABACC's accounting and control activities. For this purpose, several provisions were introduced into the Quadripartite Agreement, its Protocol, and General Part of the Subsidiary Arrangements. These provisions produced several levels of coordination between the ABACC and the IAEA and between the two organizations and the two countries. Coordination arrangements were progressively implemented during the last twenty years.

2. Legal and Political framework of ABACC

The Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) consists of a four-member Commission appointed equally by the two countries and a Secretariat with headquarters in Rio de Janeiro, Brazil. The Secretariat consists of technical and administrative professionals appointed by the Commission, clerical staff, and inspectors. The present technical staff consists of ten people, five Brazilians and five Argentineans: one Secretary, one Deputy Secretary, two planning and evaluation officers, two operations officers, two technical support officers and two accounting officers. The higher-ranking technical officer of each country alternates annually as ABACC's Secretary. One administrative and finance manager and one institutional relation complete the team of ABACC professional staff.

The inspections are performed in a cross-national basis, with Argentine inspectors verifying facilities in Brazil and vice-versa. The inspectors do not work permanently for ABACC. They are experts who usually work for the nuclear area of countries, National Authorities, or other official organizations in each country, and are convoked by ABACC's Secretariat whenever necessary. It should be noted that the team of inspectors consists not only of people working in safeguards at a national level, but also of experts from several areas of safeguards interest (NDA, DA, design and operation of nuclear installations, etc.). Presently, the inspectorate of ABACC has around 90 inspectors being half and half for each country.

Established the legal framework ABACC would have not succeeded without the political support from the Argentinean and Brazilian government and the international safeguards organizations, such as ESARDA, INMM, DoE, European Commission to name a few, that have supported, helped and encouraged this regional organization.

The economic resources required for the implementation of the SCCC and the functioning of ABACC was established, in a general way, by the Bilateral Agreement; both countries share the costs on an equal basis. The regular operational budget of ABACC is of some US$ 4 million per year (this figure does not include the salaries of the inspectors and consultants, which are borne directly by both countries). ABACC relies also on the nuclear structure of both countries to support its technical activities. Technical cooperation with other safeguards organizations also help to withhold the expenses on research and development of safeguards tools.

As a regional safeguards system, ABACC has also to fulfil its obligations and relationship with IAEA established at the Quadripartite Agreement.

The basic undertakings of the Quadripartite Agreement are:

- The acceptance by the Parties of safeguards on all nuclear materials in all nuclear activities, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices.
- The IAEA shall have the right and obligation to ensure that safeguards will be applied in accordance with the terms of the Agreement.
- ABACC undertakes to cooperate with the IAEA, in accordance with the terms of the Agreement.
- The IAEA shall apply its safeguards in such a manner as to enable it to ascertain that there has been no diversion of nuclear material to any nuclear weapon or other nuclear explosive device.
- The IAEA verification shall include, inter alia, independent measurements and observations.
- The IAEA verification shall take due account of the technical effectiveness of the SCCC.
- The signatory States, ABACC and the IAEA shall avoid unnecessary duplication of safeguards activities.

This Agreement is clear with regard to the relationship between ABACC and IAEA, mentioned in the Basic Undertakings and in various other articles. Furthermore, the four Parties have signed a Protocol specifying cooperation arrangements for the application of safeguards whose principles are:

(a) the need for ABACC and the IAEA each to reach its own independent conclusions;

(b) the need to coordinate as far as possible the activities of ABACC and the IAEA for the optimum implementation of the Agreement, and in particular to avoid unnecessary duplication of ABACC safeguards;

(c) when performing their activities, ABACC and the IAEA shall work jointly, wherever feasible, in accordance with compatible safeguards criteria of the two organizations; and

(d) The need to enable the IAEA to fulfill its obligations under the Agreement, taking into account the requirement for the IAEA to preserve technological secrets.

Additionally, the Protocol establishes a high level Four-Party Liaison Committee, responsible for coordinating the application of the Agreement and of the Protocol and which may appoint a sub-committee for the implementation of safeguards that should foster adequate coordination between the IAEA, ABACC and both countries.

During the past 20 years the four parties have agreed in a number of Guidelines, Joint Procedures, Cooperation procedures which casted the coordination of safeguards activities in the framework of the Quadripartite Agreement.

3. Technical capacity of ABACC (implementation)

To apply safeguards as an inspectorate, ABACC had to build a system which must have competence to fully develop, implement and evaluate safeguards measures. That means, this system must have human resources capacity, a set of well developed and useful safeguard equipment, a trained and knowledgeable inspectorate body and a good headquarters support system to integrate all data obtained from safeguards activities and to generate its evaluation.

The system must operate efficiently from the planning of safeguards measures, which will rely on the right safeguards approach, the preparation for the inspection, the instruments and equipment to be used to and the way that ABACC will treat and evaluate the data obtained.

The application of safeguards in the jurisdiction where ABACC operates has offered different challenges in a range of different technical aspects. The technical activities are mainly oriented to the verification of operator declarations of material inventories or facilities usage, as stated in the SCCC and in the Quadripartite Agreement signed by the parties involved.

The technical activities derived from the safeguards verification procedures in which ABACC have mainly worked can be categorized in six different areas:

- Safeguards Approaches;
- Inspector training;
- Non Destructive Assay (NDA);
- Destructive Assay (DA);
- Containment and Surveillance (C&S);
- Data management.

ABACC has been involved in the development of unique safeguards approaches which required its staff to support research efforts on the technologies available, testing of new equipment as well as to some development work.

Since ABACC was designed to get the competence and support from the States to carry out its activities, it was necessary to increase the efforts of the countries to support ABACC's activities (for instance, they need to expand their laboratories and human resources capabilities to be able to provide ABACC with the necessary support to carry out crossed inspections in the countries). This double role of the National Authorities is not new in the safeguard's field, and contributes for the effectiveness of the safeguard system. The technical support available from the two parties embraces inspectors, consultants, equipment maintenance and calibration, preparation of standards, laboratory services and any other safeguards related study or service.

That means that ABACC has to look for and manage the necessary support from the states in order to build its own system. This support shall not compromise the confidentiality of the safeguards system neither the credibility of the whole system.

ABACC has the responsibility to manage and support the necessary safeguards projects in the countries or any other institution. Even counting on the ABACC's staff composed by highly qualified and experienced technicians, ABACC does not have its own laboratories or enough technical personnel to conduct new R&D techniques for a particular application or to adapt and get acquainted with new methods and technologies to be used at the inspections.

It is also ABACC's responsibility to foster the development of the countries laboratories and expertise necessary for applying the safeguards. For instance, in order to check the status of the laboratories that analyze the samples collected by the inspectors, the ABACC technical support area keeps a permanent inter comparison program running. These comparison programs are carried out with the cooperation of other international laboratories – NBL and IAEA (Seibersdorf).

Groups of experts of Brazil and Argentina are also called by ABACC as consultants in order to discuss a particular technology whenever it is necessary. Cooperation with other institutions as DOE/USA, CEA, EURATOM, EC-JRC, IAEA, KINAC and some countries are very successful and profitable to overcome this point.

The need to have a system that could manage all data collected during the inspections and could integrate the different technical areas of ABACC led to the development of database systems that will allow the management of accountancy, technical and administrative data and the production of detailed reports related to safeguards implementation.

It is important to mention that two database systems that were developed by ABACC have special importance. One is the SJAR, an accountancy system that allows the data collected during the inspections feeds the ABACC database and checks are executed and automatic reports are generated to provide feedback on the legal flow of information. It was implemented and a Joint Use System for this software was established with the IAEA. Special files and reports are generated for feeding the IAEA database. The other system is the Operation Database System that fully integrates all planning, execution, data collected and reports from all inspection information. It is a powerful tool that is used for safeguards and technical evaluation of ABACC's safeguards system.

The technical projects are conducted together with other organizations. Indeed, it is ABACC's policy to develop new technological systems in cooperation with IAEA, which is an end user as ABACC, and with other organizations which have human resources or laboratories. Some of the projects are listed below:

Projects	Application	Hardware development	Collaboration Organizations
Safeguards Studies	Enrichment - centrifuge and gas diffusion	No	IAEA/DoE
	On load safeguards approach	No	IAEA
NDA	Gamma and neutron detection for visual restricted access points at enrichment cascades	Yes	IAEA/CNEN/DoE
	Gamma evaluation on hold up at diffusion plants	YES	IAEA/CNEA/DoE
	Neutron collar for unique type of fuel element with slight enrichment	Yes	IAEA
	System to verify a difficult to access spent fuel assemblies stored in a Spent Fuel Pond	Yes	IAEA/DoE
	U and Pu using bulk analysis	No	CNEN/ARN/DoE
	TMIS and SMIS analysis	Yes	CNEN/ARN
	Gamma Evaluation Codes for Plutonium and Uranium Isotope Abundance Measurements by High-Resolution Gamma Spectrometry	No	EURATOM/IAEA/DoE
	Software for Enrichment Measures	No	DoE
	Differential Peak Absorption (DPA) technique	No	DoE
DA	UF_6 sampling methodology with alumina pellets	Yes	CNEN/ARN/DoE/IAEA
Information System	Load cell authentication	Yes	CNEN/IAEA
Surveillance systems	Secure Video Surveillance System	Yes	DoE
	Moveable Surveillance System	Yes	CNEN/IAEA
Support Systems	Operation database	No	
	Accountancy database	No	IAEA

4. Coordination and collaboration with IAEA

In the safeguards system that succeeds the Quadripartite Agreement, four levels exist all together: the facility level, the State authority, the regional safeguards organization (the ABACC), and the international safeguards organization (the IAEA). In practical terms, all IAEA safeguards activities in the two countries are coordinated with the ABACC or through the ABACC.

The use of Regional/State Systems for international safeguards is not new. In INFCIRC/153 type comprehensive agreements, Art. 7 says that the State shall establish and maintain a system of accounting and control of all nuclear material, and the applied safeguards shall allow the IAEA to verify the findings of the RSAC. For this purpose, the IAEA shall perform independent measurements, and its verification shall take due account of the technical effectiveness of the State's system. Furthermore, the document foresees (Art. 31) that the IAEA, in its verification activities, shall make full use of the RSAC and shall avoid the unnecessary duplication of the RSAC/SSAC activities. These provisions should be reflected in the technical criteria adopted by the IAEA: INFCIRC/153 states that the criteria to determine the actual number, intensity, duration, timing and mode of routine inspections of any facility shall include the effectiveness of the RSAC/SSAC. In short, the clear purpose of all these provisions is to assign to the SSAC or RSAC the control of the facilities and to the IAEA the control of the SSAC or RSAC. This does not mean that the IAEA can not draw independent conclusions, but rather that, in order to draw independent conclusions, the IAEA does not need to repeat all the actions of the Regional System. Although the results from coordination of activities are in general satisfactory, a full implementation of the provisions of the Quadripartite Agreement is yet to be reached.

The Quadripartite Agreement establishes that ABACC and the IAEA shall apply nuclear safeguards in a coordinated and cooperative way. In order to obtain the maximum of efficiency and effectiveness, using the minimum effort and assuring independent conclusions from each organization, coordination and cooperation between ABACC and the IAEA while applying safeguards plays a major role.

In the last 20 years a significant effort was made by both Agencies to improve Coordination and Cooperation. Many accomplishes were reached in some areas, among which we can list:

a) Documentation framework area:

- Guidelines for inspection coordination between ABACC and IAEA; (coordination)
- Procedures for Common Use of Equipment; (cooperation)
- Procedures for special inspections; (coordination); (coordination)
- Procedures for secure communication between ABACC and IAEA; (coordination)
- Procedures for Nuclear Material Reporting from the States to the Agencies; (coordination)
- Procedures for specific inspections (sensitive installations). (coordination)

b) Concept and evaluation area:

- Participation in special groups concerned with particular installations. Development of safeguards approach and procedures for especial installations; (cooperation)
- Reclassification of installations by type; (coordination)
- Implementation of new policies; (coordination)
- Domestic transfer verification approach; (coordination)
- Implementation of Short Notice random Inspections; (coordination)
- Facility Attachment negotiations; (coordination)

c) Inspection implementation area:

- Planning of Inspections; (coordination)
- Inspections programming avoiding operational conflicts; (coordination)
- Optimization of PDI without loosing effectiveness; (coordination)
- The application of Joint Use of Equipment in inspections; (cooperation)
- Procedures for specific inspections (sensitive installations). (coordination)

d) Technical and operational support area:

- Planning of equipment acquisition between the Agencies; (cooperation)
- Comparison of DA analysis results; (cooperation)
- Data analysis from NDA results applied to error calculation for equipment used at facilities; (cooperation)
- Joint training on specific inspection approaches (sensitive installations); (cooperation)
- Joint training of inspector on equipment and procedures applied in inspections; (cooperation)
- To use the DA results from ABACC; (cooperation)

e) Administrative Area:

- Administrative procurement, transfer and management of samples and equipment;
- Support to inspectors in ABACC area;
- Payment and reimbursement of services provided at ABACC zone.

Most of the items listed above have been implemented and some of them will remain in "on going" status as long as the Agencies apply safeguards based on the Quadripartite Agreement. Any new subject with the potential for improving the safeguards system will become an active item in the coordination agenda.

5. Cooperation with European Commission and ESARDA

It is important to remark at this time when ABACC is celebrating two decades of existence the support and collaboration from the European Commission, particularly represented by Euratom - European Atomic Energy Community and the ESARDA - European Safeguards Research and Development Association.

At the very beginning ABACC looked for other organizations in which it should resemble and learn from its experience. Being the first regional system, Euratom emerged as the unique choice at the beginning. However, even though we had just one organization to function as a standard to implement the ABACC system, it was a surprise for ABACC's staff to verify the efficiency and competence of this regional system. It was also with a great pleasure that we could find support and partnership from our older brother.

During an extensive period ABACC took advantage of the way that Euratom system was developed and the help from Luxembourg staff in how to implement ABACC's safeguards system. Today, this spirit of collaboration remains and from time to time the two organizations get together to share their experiences. We can say that even the long distance and the slight difference on the framework have not impeded an open and fruitful collaboration between the two directorates.

ESARDA also played an important hole on the tasks realized by ABACC on the last 20 years. ABACC is an observer member at ESARDA and it is allowed to participate at the ESARDA working groups since the beginning. The collaboration on the Techniques and Standards for Destructive Analysis, Techniques and Standards for Non Destructive Analysis, Containment and Surveillance, Implementation of Safeguards and Training and Knowledge Management working groups were the more profitable examples of such collaboration. ABACC always participate at the main ESARDA events, like the annual meeting and the annual working groups' workshops.

ABACC is proud to recognise the support obtained and friendship developed with these high level international safeguards institutions.

6. Lessons learnt

It is not easy to summarize the experience and lessons learnt by a regional system in its first 20 years of existence. Some of the features are subjective and the experience is laying on the culture of the institution. However, we may state a few points:

- The exact role of ABACC in the non-proliferation profile of the two countries. Even though the non-proliferation status is a characteristic that the state has to gain or show, ABACC function as tool for that purpose and it has to act always as an organization that contribute for such objective;
- The relationship among the States and ABACC and the IAEA and ABACC is unique. ABACC plays in the middle of these players and ABACC has to balance the exact hole as a regional system, understanding the peculiarities of the countries and the requirements of an international system that tends to be uniform and mechanistic;
- The IAEA needs the support of other safeguards systems to accomplish its tasks;
- The new trends on international safeguards and the new technologies should be absorbed by ABACC and after the right understanding they should be transmitted to the states;
- To guarantee the credibility of the system, ABACC has to be independent of the states political line and at the same time to have it own technical criteria (which sometimes may be different from those of the IAEA);
- The most important characteristic of ABACC is its own technical competence and the acknowledgement of this competence by the international safeguards community;

7. Future Trends

ABACC considers of fundamental importance and fully supports IAEA initiatives to define the conditions and activities pursuant to the implementation of State-level concept. The definition of State-specific safeguards objectives to be applied to a State and to use the current Safeguards Criteria as a menu of safeguards tools, not as a prescriptive requirement for safeguards application, is also supported by ABACC. In particular, ABACC considers that some basic documents should be prepared for the appropriate consideration of the regional safeguards international system, in particular:

a) A complete description of the methodology for determining the State-specific Safeguards Technical Objectives that are intended to be used for a State safeguards evaluation. Such a description would allow to consider alternative safeguards activities for covering these objectives and facilitate the proper introduction of new safeguards tools, either because of new techniques (e.g. remote monitoring, environmental sampling) or because use is made of RSAC or SSAC resources.

b) A scheme of the rules and criteria to be used for evaluating the objective elements of an RSAC or SSAC. This will allow both the IAEA to consider the eventual “delegation” of some verification activities and the RSAC or SSAC to consider improvements of its system for a better inclusion into the integrated scheme.

c) A summary description of the basic rules that would be used to consider the less quantitative elements that shall be considered for evaluating the credibility and effectiveness of RSAC and SSAC. This will allow the States and the RSAC or SSAC to understand logical differences in the application of the state level concept as well as to promote changes aimed at increasing credibility and effectiveness of the local system.

d) A summary description of the basic scheme of the quality assurance program to be used by the IAEA to confirm, on a continuous basis, that the RSAC or SSAC maintains its initial credibility and effectiveness. This will allow the States and the RSAC/SSAC to be prepared for an extensive integration. It should be noted that increase integration would imply, inter alia, the presence of IAEA inspectors at the RSAC or SSAC headquarters for long periods of time or the sudden incorporation of an IAEA Inspector to an ongoing RSAC/SSAC inspection at a given facility.

8. Final remarks

The successful projects developed by ABACC and its partners in this field of safeguards have contributed to the application of safeguards in a more effective and efficient way contributing for non-proliferation. The ABACC Secretariat is proud to complete the 20th anniversary with an organization that is recognized for excellence in international safeguards. New challenges are coming for the years ahead, and the initial spirit and strength of ABACC organization remains for facing these challenges.

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Peer reviewed section

Quench gas and preamplifier selection influence on ^{3}He tube performance for spent fuel applications

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Abstract:

Current ^{3}He tubes utilized in neutron coincidence counting use different quench gas admixtures to shorten the avalanche process. In addition amplifier modules with different shaping characteristics are used to process detector signals. Both of these aspects affect the detector response. In the current paper, ^{3}He tubes with several quench gas admixtures (CO_2, N_2, Ar+CH_4 and CF_4) and amplifier modules (PDT, AMPTEK, BOT) are compared. The plateau characteristics, gamma-sensitivity and dead-time of individual counters in combination with the listed amplifier modules are compared to determine optimum amplifier module/counter performance for the spent fuel applications.

Keywords: plutonium content, spent fuel, ^{3}He count rate capabilities, NDA

1. Introduction

The Next Generation Safeguards Initiative (NGSI) of the U.S. DOE has initiated a multi-laboratory/university collaboration to quantify the plutonium (Pu) mass in, and detect the diversion of pins from, spent nuclear fuel assemblies with non-destructive assay (NDA) techniques. The goal of this research effort is to improve the technology base of safeguards.

Safeguarding and determination of plutonium mass in spent fuel assemblies represents a very challenging task due to high gamma and neutron contributions from accumulated fission products and actinides that mask the fissile content signatures. The surface gamma-ray dose of a typical spent fuel assembly can reach levels as high as 10^5 R/hr. Use of lead shielding can reduce the dose to 1-10 R/hr at the detector face, which still represents levels not typically encountered in traditional safeguards. Thus a detection system with low gamma sensitivity is desirable. In addition a fast detection system is required, capable to handle rates of the order of 10^6-10^7 counts per second. Recently developed Differential Die-Away Self-Interrogation (DDSI) technique [1] aims to provide plutonium mass information based directly on the measurement of spontaneous fission neutrons from ^{244}Cm and induced fissions in the sample. The technique utilizes the doubles/singles ratio and the early and late counting gates to determine the fissile content from the ratio of count rates in these two gates. This ratio is subsequently related to plutonium mass using weighted contributions from three major fissile isotopes (^{235}U, ^{239}Pu and ^{241}Pu). The need to provide a good separation between the early and late gates in the DDSI technique together with high count rate requirements places tight limits on timing characteristics of neutron detection system.

Traditional neutron coincidence counting utilizes ^{3}He based proportional counters, which are favoured for their high stability, efficiency of neutron detection and low gamma sensitivity. Nevertheless, in order to operate a ^{3}He based counter in the demanding conditions such as spent fuel applications, its gamma sensitivity and count rate capabilities need to be optimized. In the current investigation, we focus on the influence of different types of quench gas and signal processing electronics on the performance of the ^{3}He based system.

The primary role of quench gas is to suppress photo-emission caused by de-excitation of atoms of the fill gas and related secondary electron emission. In addition, the choice of gas affects the electron/ion mobility and thus detector pulse shape characteristics. Presence of quench gas molecules contributes to increase in electron drift velocities and increase of the stopping power of ^{3}He(n,p)^{3}H reaction products. Typical electron drift time in the 1" diameter ^{3}He-based counters corresponds to hundreds of ns to few μs. The ion drift time contributes to a long component of the signal of hundreds of μs [2]. The type and amount of quench gas will affect the electron/ion mobility and thus the charge collection time. Different types of quenching molecules are used based on application needs. The most typical in neutron coincidence counting applications is an Ar+CH_4 quench gas due to its favourable count rate characteristics [3]. However, due to the high *Z* of Ar, it is more sensitive to gamma interactions [4]. In addition CO_2 or N_2 quench gas admixtures are frequently used, which were shown to be capable to operate in increased gamma backgrounds with similar performance [5]. Nevertheless, N_2 quench gas admixture results in longer pulses, which can limit its count rate capabilities. A use of CF_4 quench gas was suggested as a possible candidate to exhibit lower gamma-ray sensitivity [6] and higher electron drift velocity [7], which are favourable characteristics for spent fuel applications.

The signal processing electronics can be optimized to achieve desired signal characteristics and count rate capabilities for given application needs. The type of shaping and shaping time constants will influence the gamma pile-up rejection as well as count rate capabilities of the system. Short shaping time constants result in faster decay times of the detected pulses and allow the system to be operated at higher count rates. Additionally short shaping times reduce contribution of gamma pileup relative to neutron pulses. The most frequently used signal processing electronics in combination with ^{3}He-based counters are AMPTEK and Precision Data Technology (PDT) amplifier modules. In addition the amplifier modules manufactured by BOT Engineering Ltd. are considered for safeguards applications by the IAEA.

In order to evaluate capabilities of different ^{3}He proportional counters for spent fuel applications we performed a dedicated experimental evaluation of 1" diameter ^{3}He counters with several different quench gas admixtures (CO_2, N_2, Ar+CH_4 and CF_4). Each ^{3}He counter was combined with each of the amplifier modules (PDT, AMPTEK, BOT). The high voltage (HV) plateau, gamma sensitivity and dead-time characteristics of individual counters in combination with the listed amplifier modules were evaluated.

2. Experimental evaluation

Four ^{3}He counters with CO_2, N_2, Ar+CH_4 and CF_4 quench gas admixtures were evaluated. Each counter was 12" long with 1" diameter and fill gas pressure of 4 atm. Each counter was combined with standard AMPTEK-A111, PDT-10A and BOT amplifier modules.

The AMPTEK-A111 hybrid charge-sensitive preamplifier-amplifier-discriminator module [8] has bipolar shaping with very short time constant of the order of 190 ns. A gain adjustment on the range of ~ 10:1 is provided through 20-KΩ potentiometer. The nominal sensitivity corresponds to 8 fC. The PDT amplifier module is available in many different application specific versions. In current testing the PDT-10A version with bipolar shaping and shaping time of ~500 ns was utilized [9]. The PDT amplifier module provides gain as well as threshold adjustments. The threshold is typically set by the manufacturer to provide a minimum of 0.015 pC sensitivity. The gain setting can be used to further adjust the sensitivity by about a factor of 20:1. In the current activity, only the gain setting of PDT amplifier was modified. The PDT-10A is used in many ^{3}He based neutron coincidence counters and thus serves as a good performance reference. The BOT amplifier module was designed for use with wide variety of proportional counters [10]. The unit used in the reported test activity provides a unipolar shaping with 2.5 μs shaping time. The gain (in the range of 6:1) as well as threshold adjustment is provided. All the amplifier modules provide analog inspection signal to view the shaping characteristics. A discriminator TTL output is provided that can be directly connected to the data acquisition electronics. A standard multiplicity shift register (JSR-15) [11] was used to collect the digital signal. AMPTEK as well as PDT amplifier modules allow adjusting the width of the discriminator output; ~ 50 ns is typically used in the NDA applications. The duration of the discriminator output pulse in BOT amplifier module is fixed in the circuit design, but can be modified by the vendor. In the current test activity the gain of each amplifier module was adjusted to correspond to an optimum performance of the ^{3}He-CF_4 tube. For this purpose the gain of each amplifier module was modified in a very limited range, where the amplifier response remains linear. The linearity of amplifier response assures that the selected electronics setting combined with other quench gas admixtures will not affect the investigated gamma sensitivity and dead-time characteristics.

During the measurement each counter was placed in a cylindrical polyethylene block and irradiated by a 98 μCi ^{252}Cf source. Each counter/electronics combination was tested for the shape of high voltage plateau, gamma sensitivity and dead-time. During the HV plateau and gamma sensitivity measurements the TTL output was recorded using JSR-12. To evaluate system dead-time the TTL output was recorded in list mode to allow for data recording on event-by-event basis. Using this information a time interval analysis was utilized to extract dead-time information for each counter/electronics combination. To record data in list mode, a List Mode Multiplicity Module developed at LANL was used [12].

2.1. High voltage plateau

High voltage plateau was measured for each counter/electronics combination in the range of 1200 V – 2000 V in 20 V increments. Based on this information, an operating voltage for every system was determined as 40 V into the plateau, above the knee. The HV plateau results for the four quench gas admixtures and tested amplifier modules are summarized in Figure 1.

Differences between the quench gas admixtures are clearly visible in Figure 1. A very long and stable plateau is observed in case of CF_4 quench gas for all the amplifier modules used in the test. The slope of the plateau is better than 0.5 %/100 V. The Ar+CH_4 as well as N_2 quench gas admixtures, when connected to AMPTEK-A111 amplifier module, exhibit an onset of a second hump on the plateau. This hump can be attributed to multiple triggering of electronics on a single neutron capture event. Variation of ionization tracks traversing ^{3}He counter translates into complex structures present in the detector current pulses. Due to the short shaping time in the amplifier the discriminator can

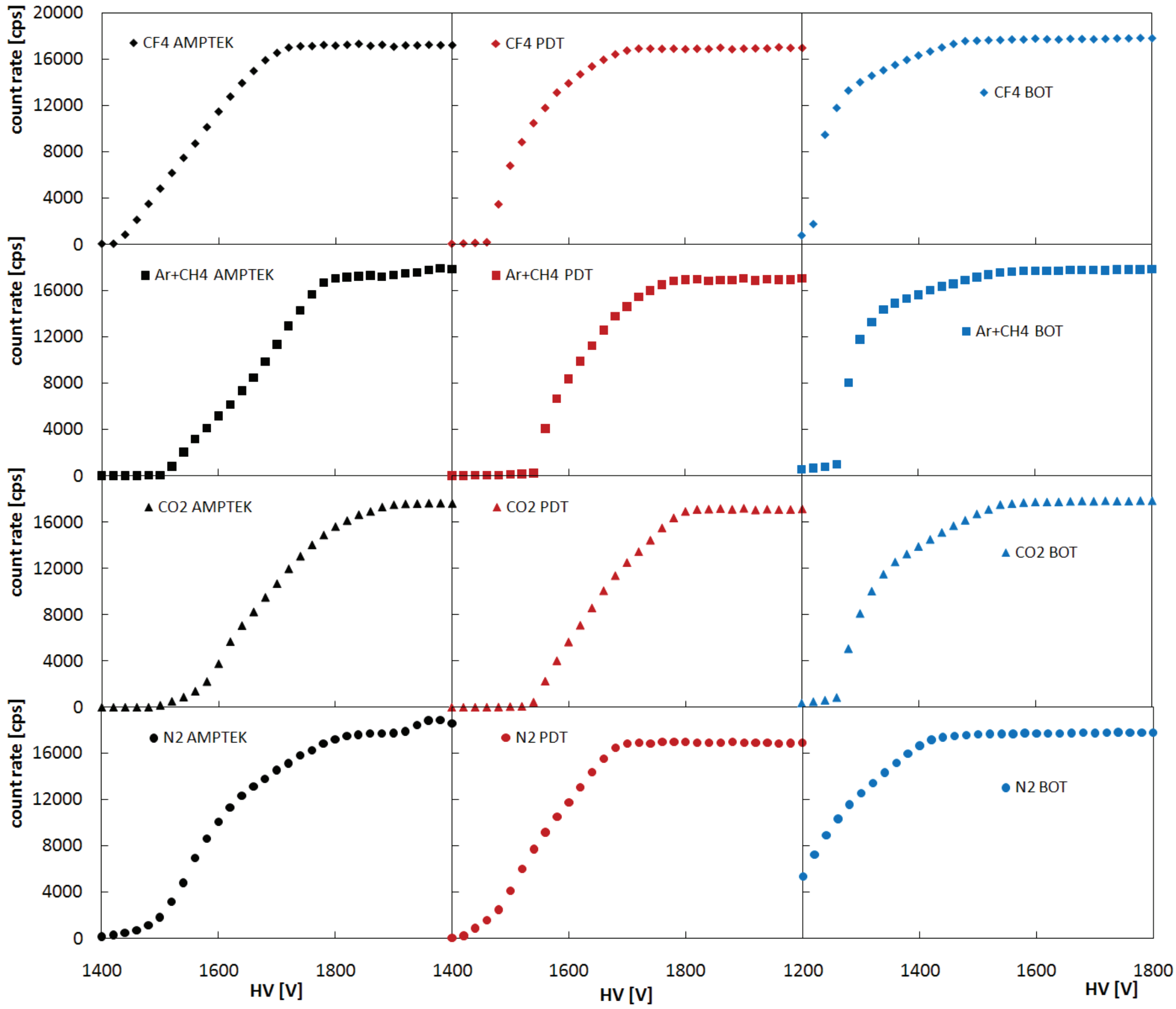

Figure 1: Comparison HV plateaus measured using ³He counters with Ar+CH_4, CF_4, CO_2 and N_2 quench gas admixtures. Results were acquired using AMPTEK-A111 (left), PDT-10A (middle) and BOT (right) amplifier module. Note different x-axis in case of BOT amplifier module.

re-trigger on these structures formed in a single event. This effect is more pronounced in case of N_2 gas. The operational high voltage is normally set below the level where this effect becomes important. As can be seen from comparison with PDT and BOT amplifier modules the second hump is removed when longer shaping time electronics is used.

Figure 1 also illustrates influence of different signal processing electronics on the shape of HV curve. A well defined plateau is observed for all the quench gas admixtures combined with PDT-10A or BOT electronics. As noted above, fast shaping time of the AMPTEK-A111 affects the response of Ar+CH_4 and N_2 quench gasses by additional hump on the plateau. In addition the shape of the HV plateau is no longer well defined in case of N_2 quench gas when combined with AMPTEK amplifier module. This is a consequence of interplay between the short time constant of the AMPTEK shaper and longer collection time of this quench gas admixture. Thus use of AMPTEK amplifier module with this quench gas admixture is not advisable.

Use of different amplifier modules also affects the extent of the HV plateau and shape of the slope of the initial count rate increase with increasing HV. These differences can be attributed to the differences in the types and time constants of the shaping electronics. The shaping type and time constant of an amplifier influences the signal amplitude and thus the shape of a pulse height spectrum. With shorter shaping times, a smaller portion of the input charge pulse is integrated resulting in incomplete energy information. The short shaping time causes deterioration of full energy peak in the pulse height spectrum and increased contribution of low energy pulses. With increasing shaping time, more complete charge integration is performed, which allows preserving complete energy information for sufficiently long shaping. The differences in the shapes of the pulse height spectra translate into the HV plateau as observed in Figure 1. The long shaping time of BOT amplifier module allows for preserving the most complete energy information, thus a sharp initial increase in count rate with HV followed by a smooth transition into the plateau region is observed.

2.2. Gamma sensitivity

To evaluate the gamma sensitivity of each counter/electronics combination measurements were performed using ^{137}Cs sources of ~450 mR/hr gamma dose rate at the detector face. The combined dose rate of the ^{137}Cs sources is the maximum dose rate available under our laboratory conditions. The HV curve results are compared to bare neutron source data in Figure 2.

An increase of count rate due to gamma-ray pileup is clearly visible in Figure 2 for all the quench gas admixtures. Comparing different quench gas admixtures it can be seen that CO_2 and N_2 combined with BOT electronics result in the longest plateau before an onset of gamma pileup, which corresponds to ~ 200 V. The length of the plateau in case of Ar+CH_4 and CF_4 admixtures is slightly reduced and corresponds to ~ 160 V. The onset of gamma pileup is similar for all the quench gas admixtures when using PDT amplifier module. The length of the plateau in this case corresponds to ~ 120 V in case of CO_2 and N_2 and to ~ 100 V in case of Ar+CH_4 and CF_4 quench gas admixtures. A very short apparent plateau before an onset of gamma pileup is observed for CO_2 and N_2 quench gas admixtures combined with AMPTEK amplifier module. This is a consequence of an earlier observation that the use of the AMPTEK amplifier module does not provide good plateau characteristics for these gas admixtures. The gamma sensitivity of Ar+CH_4 and CF_4 quench gas admixtures when combined with AMPTEK amplifier module is similar as in case of PDT electronics.

Due to the higher *Z*, Ar gas is expected to be more sensitive to gamma pileup than lighter CF_4 molecule. The similar gamma sensitivity observed for of both quench gas admixtures suggests that the effect is dominated by the interactions in the counter walls and fairly insensitive to the type of quench gas.

2.3. Dead-time

Another parameter crucial to achieve high count rate capabilities is the system dead-time. Dead-time is a complex

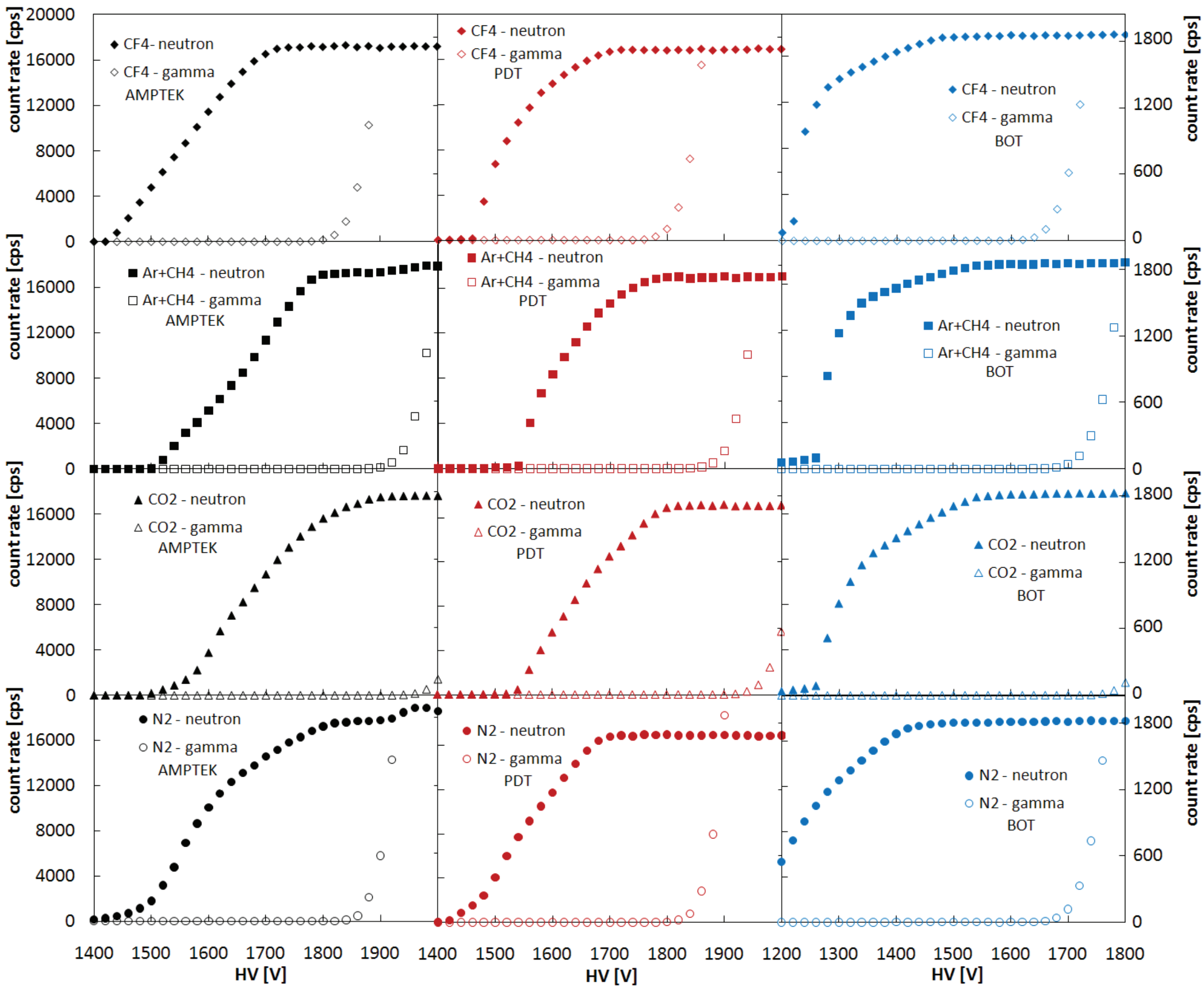

Figure 2: HV plateau measured with ^{252}Cf source (full symbols) and using ^{137}Cs sources of ~450 mR/Hr dose rate at the detector face (open symbols) for all the quench gas admixtures and electronics combinations investigated. Note different scale on x-axis in case of BOT amplifier module. The count rate corresponding to gamma events is shown over an expanded range (right vertical axis).

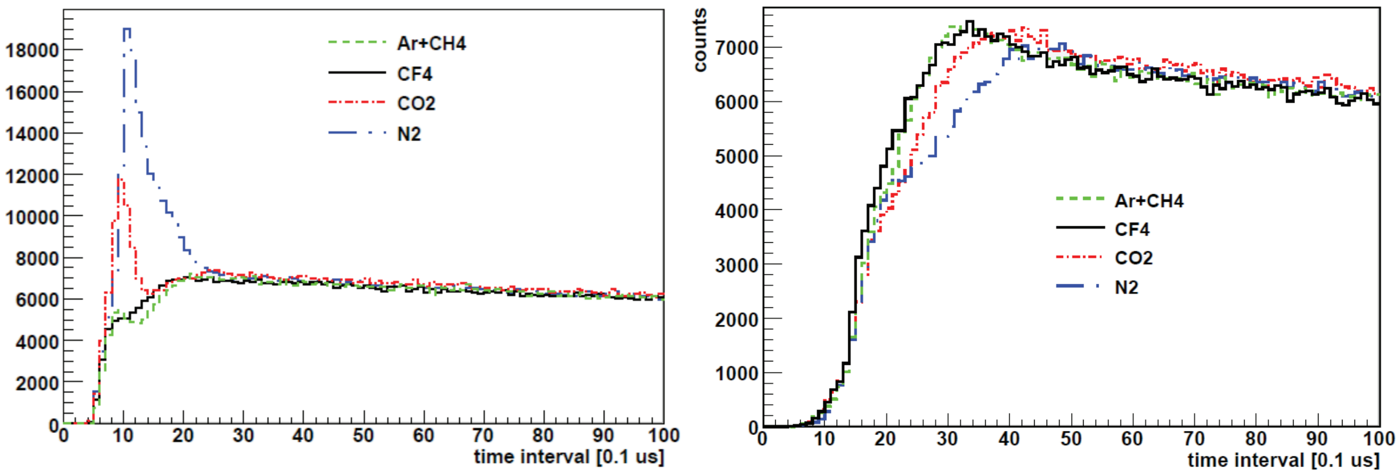

Figure 3: Time interval analysis results for Ar+CH_4, CF_4, CO_2 and N_2 quench gas admixtures with AMPTEK-A111 (left) and PDT-10A (right) amplifier modules.

function of the system parameters and is affected by the properties of the counter (such as detector fill gas or applied HV) as well as by signal processing electronics (such as shaping time and type of shaping). Use of list mode data acquisition allows a direct investigation of dead-time in the detection system. Dead-time information can be extracted from time interval analysis of list mode data, where frequency of occurrence of a given time interval between two subsequent pulses is evaluated.

Dead-time was evaluated for each counter/electronics combination using a ^{252}Cf source. Comparison of time interval distributions for the four investigated quench gas admixtures in combination with AMPTEK-A111 and PDT-10A amplifier module is shown in Figure 3 (left) and (right), respectively. Comparison of influence of signal processing electronics on time interval distribution is shown in Figure 4.

Figure 3 provides an overview of influence of different quench gas admixtures on the system dead-time. It can be seen that the minimum interval before a second pulse can be detected, which represents system dead-time, corresponds to ~ 600 ns and ~ 1.6 µs in case of AMPTEK and PDT electronics, respectively. This interval is largely independent of the type of quench gas. Nevertheless, the short time-interval range in case of AMPTEK amplifier module is dominated by a pronounced spike in case of CO_2 and N_2 admixtures. However, much less pronounced, structure is apparent in the case of Ar+CH_4 quench gas. This spike is a consequence of the interplay of short shaping time of the AMPTEK amplifier module and different charge collection times from the investigated quench gas admixtures.

The products of neutron interaction in the ^{3}He gas can traverse the proportional counter in various directions causing spread in the rise time of charge pulses from the detector. The shortest rise times correspond to ionization tracks parallel to anode wire. The charge pulse spread is transformed into variation of shapes and amplitudes of current pulses, which can reveal complex structures with multiple humps. These structures are apparent in particular in case of tracks oriented perpendicular to the anode wire. Due to the short time constant of AMPTEK shaping amplifier, its output pulse is dominated by the structures present in the detector pulse. Therefore a re-triggering of discriminator on the complex pulse structures can be expected, which causes false events. The spike on the timescale of approximately 1 µs observed in Figure 3 (left) is likely a consequence of this effect. The importance of discriminator re-triggering can be eliminated by use of a longer shaping time as shown in Figure 3 (right) in case of PDT-10A amplifier module with shaping time of ~500 ns.

The elimination of the re-triggering effect is especially important in neutron coincidence counting as the contribution of the false pulses can affect the coincidence rate. As can be seen from Figure 3, the re-triggering contributes on the timescales of ~ 1 µs. Standard neutron coincidence counting utilizes shift register electronics [13], where a fixed predelay of few µs is used to remove deadtime effects on the short timescales before the coincidence counting commences. The predelay also helps eliminating the effect of re-triggering in the coincidence rate. In addition, the use of proper quench gas can help mitigate this effect even in combination with fast timing electronics such as AMPTEK. Indeed, the effect is significantly reduced in case of CF_4 admixture due to fast charge collection characteristics of this quench gas. Therefore, combining the ^{3}He-CF_4 gas with fast timing characteristics of AMPTEK is a feasible option to improve the system dead-time.

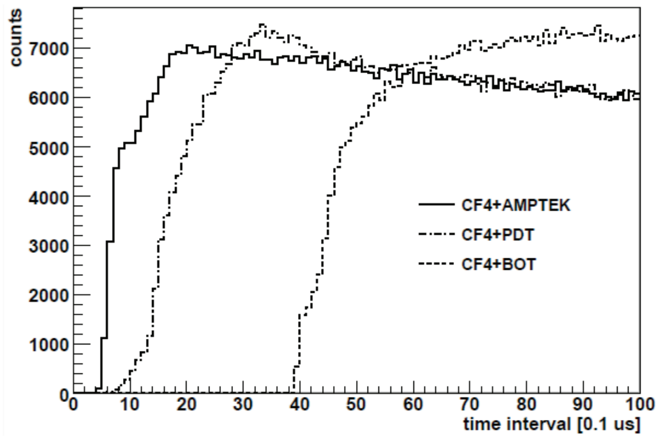

Figure 4: Time interval analysis for ^{3}He counter with CF_4 quench gas and different signal processing electronics.

Figure 4 shows a comparison of time interval distributions for CF_4 quench gas and different signal processing electronics. A clear effect of signal processing electronics on the system dead-time can be seen from the figure. The shaping characteristics and short shaping time of AMPTEK result in the fastest system response with shortest dead-time of the order of 600 ns. The longer shaping time characteristics of PDT-10A amplifier module cause a slower system response with dead-time closer to ~ 1.6 µs. The tested BOT amplifier module with internal shaping time of 2.5 µs results in the longest dead-time of the order of 4 µs. Figure 4 illustrates importance of optimizing the electronics for the high count rate capabilities. From the tested amplifier modules, AMPTEK in combination with CF_4 quench gas provides the most favourable timing characteristics. Nevertheless, the shaping time constants of PDT and BOT amplifier modules can be customized by manufacturer to allow shorter shaping times.

3. Discussion and conclusions

Results of the quench gas/electronics comparison presented in this paper clearly indicate the importance of optimization of the type of quench gas and signal processing electronics for spent fuel applications. In the spent fuel applications, detectors will be exposed to extreme environments not encountered in typical safeguards use for which existing techniques were optimized. Specifically improvements in gamma-ray sensitivity and count rate capabilities are highly desirable. As noted earlier, the use of CF_4 quench gas was suggested as a possible alternative to provide lower gamma sensitivity and faster response than other traditionally used quench gas admixtures [6,7]. In the current investigation a 4 atm ^{3}He counter with CF_4 quench gas admixture was evaluated against other typical quench gas admixtures. The concentration of CF_4 quench gas was optimized by manufacturer to provide comparable gain to a typical counter utilizing $Ar+CH_4$ quench gas.

The comparison of HV plateau from investigated quench gas admixtures showed that the CF_4 quench gas exhibits a very stable (< 0.5 %/100 V) and long plateau. Contrary to N_2 and $Ar+CH_4$ admixtures no double counting increase was observed in case of CF_4 quench gas. Considering the high heat output of a typical spent fuel assembly, the stable plateau of CF_4 suggests a very good long term and environmental stability can be expected in case of this counter. Gamma sensitivity of the investigated counters was evaluated at app. 450 mR/hr dose rate at the detector face – the maximum dose rate available under our laboratory conditions. It was found that the ^{3}He-CF_4 gas exhibits very similar gamma sensitivity as ^{3}He-$Ar+CH_4$ gas despite the high *Z* of argon. This observation is likely a consequence of gamma interactions in the counter walls. Thus, it can be expected that in high gamma fields ^{3}He-CF_4 gas fill will exhibit similar behaviour as ^{3}He-$Ar+CH_4$.

As shown in Figure 5, the signal processing electronics has a strong influence on the system dead-time and thus on the achievable count rate capabilities. By selecting a faster electronics time constant, the energy resolution of the system may be compromised. However, in neutron coincidence counting only arrival times of individual pulses are recorded and used to determine sample parameters based on observed correlations. In the case of spent fuel applications, the high count rate capabilities are paramount for successful measurements. Thus, the selection of the signal processing electronics for spent fuel applications needs to reflect these requirements. As shown in the current investigation, the choice of electronics has a strong influence on the system timing characteristics. Short time constants of the shaping electronics clearly result in shorter dead-times. Combination of fast timing in electronics with fill gas with fast electron drift velocity/short ion track length results in the most favourable timing characteristics as seen in case of CF_4 quench gas.

It should be pointed out that current investigation focused on commercially available amplifier modules that are typically used in NDA applications as these will provide the most likely short term electronics solution for spent fuel applications. Nevertheless, as current results illustrate the importance of signal processing electronics on the system performance, a more comprehensive evaluation of signal processing electronics in conjunction with ^{3}He-based system should be performed. Such an evaluation would enable dedicated optimization of electronics parameters such as shaping time, gain or threshold to match the required detector performance. Similar evaluation is currently underway at LANL [14].

Overall, the use of ^{3}He-CF_4 filled counter results in very long and stable plateau allowing for stable operation under varying environmental conditions. In addition, the use of CF_4 quench gas and AMPTEK amplifier module with short time constant provides the best timing characteristics of all the systems investigated. Thus, although the gamma sensitivity of CF_4 quench gas is comparable to $Ar+CH_4$, its short dead-time and very good stability make it the most suitable choice for the spent fuel applications among the investigated quench gas/electronics combinations.

4. Acknowledgements

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Estimating the Dieaway Time and its Precision from Shift Register Data

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Abstract:

Neutron coincidence counting is widely used throughout the nuclear fuel cycle to quantify special nuclear materials that fission, for example Pu. Before calibration and setting to work, instruments undergo a range of performance and characterization tests that typically include measurement of the neutron dieaway characteristic. The neutron dieaway characteristic is a general measure of the likelihood that a neutron will be detected following another neutron, and describes time behavior of detected neutrons in the assay system. This paper shows how the effective 1/e-capture dieaway time of the observable coincidence (doubles) rate may be extracted simply and quickly from two coincidence counting rates recorded with different shift register time gate settings. In particular we address how to assign the precision to such estimates including when the rates are correlated.

Keywords: NDA; neutron coincidence counting; shift register; dieaway time; precision; covariance

1. Introduction

This paper is concerned with an aspect of neutron correlation counters. Neutron correlation (both coincidence and multiplicity) techniques are widely used to assay special nuclear materials through their distinctive fission neutron time signature [1]. This is manifest by clusters or bursts of time correlated events appearing on the detected pulse train as a result of neutrons from a common fission chain ancestry remaining correlated in time as they undergo moderation, migration and detection in the detector system. The capture time distribution of a neutron coincidence counter (NCC) is conventionally summarized by an effective 1/e-capture dieaway time. The dieaway time is a useful characteristic to measure. It represents the physical distribution of neutron detection probability of subsequent neutrons following the detection of a neutron. The detector responds to the population of neutrons established inside of it and the capture time distribution describes the temporal behavior of neutrons available for capture in the sensitive volume. Every neutron may be taken as the first, trigger or time $t = 0$ neutron, and the capture time distribution is the average or expectation value of the subsequent time sweep. For NCC instruments of a given type it provides an additional consistency check that the physical build is as expected, consistent with historical performance data on units of the same design. For a new design the dieaway time may be used as part of a description which helps establish a generic performance figure of merit (related to efficiency and dieaway time) useful for roughly comparing one assay system to another. The dieaway time may be compared to design calculations to gain confidence in the design process again verifying the construction but also confirming the performance modeling. Traditionally the dieaway time is not explicitly used in the quantitative data analysis step, although some dead time correction formulations may use the concept of approximate exponential decay of the neutron population inside the detector in expressing how bursts of neutrons are detected as a function of time. But the appropriate value to use for this purpose in combination with the choice of dead time parameter comes from separate and specific set of measurements.

The purpose of the present paper is to describe an approach that has been used by the Safeguards Science and Technology Group at LANL for many years, and is also an established part of safeguards inspector training in Europe, but for which no formal description has been given in the literature, and in Europe safeguards inspectors have been exposed to these concepts. Furthermore, a method to propagate counting uncertainties is included, which is necessary to judge whether dieaway characteristics measured at two different times are consistent or have changed. We are not disparaging of more sophisticated curve fitting approaches for specific purposes, and we shall not discuss here how to interpret multiplicity (triples rate data). Our objective is rather to describe and extend a simple practice that provides a useful system characteristic commonly measured as part of preliminary instrument performance testing and characterization. For both the comparison of “instrument families” and “state of health monitoring” other complementary measured quantities, such as a measure of the neutron detection efficiency, are also vital.

2. Theory

The following formalism derives from traditional shift register sampling of a neutron pulse train using signal-triggered counting gates. This form of sampling is implemented in commercially available shift registers such as the familiar JSR12, JSR14, JSR15 or AMSR. It may also be emulated by post-processing arrival time information acquired using a list mode data acquisition system. In the signal-triggered approach each arriving pulse opens a counting gate of duration T_g that is used to count real (or genuine) and accidental coincidences. The counting gate T_g is preceded by a short, fixed predelay T_p that allows transients in the electronics that take place on very short timescales after the trigger to dissipate. The accidental contribution to the measured coincidences is determined using random gates opened after a fixed long delay following the signal trigger. In other words, events that fall within the accidentals gates are considered to be sufficiently far apart in time from the trigger not to be related to it. In the modern shift registers a fast accidentals option is implemented, where a fixed clock frequency is used to sample the pulse train and generate the accidental multiplicity distribution. Use of this technique improves the accuracy of the measured coincident rates [2]. In this framework, the measured doubles count rate may be expressed as:

$$D = D_\infty f_d \tag{1}$$

where D_∞ is the doubles rate, which would theoretically be obtained with perfect gating, that is with a predelay T_p of zero length and a coincidence gate width T_g that extend to infinity, it equates to all of the available correlations on the pulse train and available for sampling; f_d is the doubles gate utilization factor which accounts for the fact that not all the event triggered coincidences (also called pairs or reals for short) present on the pulse train are detected due to the use of a non zero predelay and finite gate. f_d thus represents the fraction of doubles present on the pulse train that get recorded by the shift register.

For a neutron coincidence counter free from electronic bias and which exhibits a single exponential capture time distribution we have [3]:

$$f_d = e^{-T_p/\tau}(1 - e^{-T_g/\tau}) \tag{2}$$

where τ is the effective 1/e-dieaway time. Recall that the shift register triggers off detected neutrons. The capture time distribution for a burst of neutrons released at the same moment in the detector therefore describes the average probability that neutrons will interact in the detector medium per unit time after the first recorded event. For moderated 3He proportional counters the detected neutrons are essentially thermalized and so the dieaway time is a measure of the lifetime of thermal flux established in the moderator. The presence of an item in the detector can modify this picture somewhat and the use of high pressure 3He proportional counters which can detect a fraction of epi-thermal neutrons also exerts an influence. Since detector systems comprise various materials and have irregular finite structures it is to be expected that several time constants are present in reality. But by careful design a strong prominent mode is usually established and an effective dieaway time is sufficient to label the detector. In fine detail one can map out the capture time distribution using different effective values over different temporal regions. The exponential model is therefore a useful one.

For an exponential time distribution and a fixed predelay and fixed correlated neutron source we see that the doubles rate as a function of gate width is expected to behave as follows:

$$D = C(1 - e^{-T_g/\tau}) \tag{3}$$

where C is a constant dependent on the source.

Suppose we perform two counts with gate widths of G_1 and $G_2 = mG_1$ where m is a convenient multiplier ; G_1 and m are chosen such that the two counting rates are sufficiently different to be determined accurately but not so large that the assumption of exponential decay, as discussed above, breaks down. Under these conditions we find:

$$\left(\frac{D_2}{D_1} - 1\right) = \frac{(1-e^{-G_2/\tau})-(1-e^{-G_1/\tau})}{(1-e^{-G_1/\tau})} = e^{-G_1/\tau}\frac{(1-e^{-(m-1)G_1/\tau})}{(1-e^{-G_1/\tau})} \tag{4}$$

In the special case that we pick $m = 2$ the expression simplifies considerably and we obtain:

$$\tau = \frac{-G_1}{ln\left(\frac{D_2}{D_1}-1\right)} \tag{5}$$

This simple result provides a way for extracting τ from suitable tabulated experimental data without the need for curve fitting. The quality of the result depends on how well the model describes the actual temporal behavior over the region selected and this can be tested by using various values of G_1 to span the broader dynamic range of interest.

We may take the value of G_1 (and G_2) in this method to be exact, however the result for τ is uncertain because the two counting rates D_2 and D_1 are subject to statistical counting uncertainty. It is important to estimate the uncertainty in the extracted dieaway to confirm that the estimate is reasonably bounded and can be reasonably taken to be reproducible. Traditionally the gate parameters are set in hardware and so D_2 and D_1 are obtained from independent measurements and the standard deviations may be estimated from cycle data. If list mode data acquisition (time stamping) is used, where the time of arrival of each pulse on the pulse train is recorded and analyzed offline, then D_2 and D_1 are correlated since they are derived from the same physical pulse train and so we cannot ignore the covariance between them. In other words, the convenience of having to perform only a single measurement has the consequence that the data analysis must be refined. But this is quite straightforward and, as we shall see, reduces the uncertainty on the result. The Pearson product-moment correlation coefficient $\rho(D_1, D_2)$ may be estimated from the list mode data by analyzing the pulse train as a series of shorter segments. Using the "bra"-"ket" notation to denote sample mean quantities we have:

$$\rho(D_1, D_2) \equiv \frac{cov(D_1,D_2)}{\sigma_{D_1}\sigma_{D_2}} \approx \frac{\langle(D_{1i}-\langle D_1\rangle)(D_{2i}-\langle D_2\rangle)\rangle}{\sqrt{\langle(D_{1i}-\langle D_1\rangle)^2\rangle\langle(D_{2i}-\langle D_2\rangle)^2\rangle}} \quad (6)$$

where σ_{D_1} and σ_{D_2} are the standard deviations in D_1 and D_2 respectively and D_{1i}, D_{2i} correspond to doubles rates from individual cycles.

The counting uncertainty in our estimate for τ may be obtained from the usual rules of propagation of variance under the normal assumption of linearization of the function over the region that the parameters may reasonably fluctuate. That is:

$$\sigma_\tau \approx \sqrt{\left(\frac{\partial\tau}{\partial D_1}\right)^2 \sigma_{D_1}^2 + \left(\frac{\partial\tau}{\partial D_2}\right)^2 \sigma_{D_2}^2 + 2.\frac{\partial\tau}{\partial D_1}.\frac{\partial\tau}{\partial D_2}\rho(D_1, D_2).\sigma_{D_1}.\sigma_{D_2}} \quad (7)$$

Performing the necessary partial differentiations we find on back substituting the following result for the relative standard deviation in τ:

$$\left(\frac{\sigma_\tau}{\tau}\right) \approx \left[\frac{\tau}{G_1}\frac{D_2/D_1}{D_2/D_1-1}\right]\sqrt{\left(\frac{\sigma_{D_1}}{D_1}\right)^2 + \left(\frac{\sigma_{D_2}}{D_2}\right)^2 - 2.\rho(D_1, D_2).\frac{\sigma_{D_1}}{D_1}.\frac{\sigma_{D_2}}{D_2}} \quad (8)$$

When the two counts are independent, as they are in separate experiments, then the correlation coefficient $\rho(D_1, D_2)$ becomes zero and the expression simplifies accordingly. Note, in Equations (6)-(8) we have used the sign ≈ in place of the = sign merely to emphasize that these are estimated quantizes derived from experimental data rather than true expectation values which would require the limit to be taken over many repeat determinations.

In applying the methods we need to decide what value(s) of G_1 to adopt. To obtain a good estimate on suitable values of G_1 to be used in Equation (5) a few considerations should be taken into account. When a strong source is used such that the uncertainty in the doubles rate is dominated by the accidental subtraction it may be shown [4] that the relative uncertainty on the doubles rate is lowest when the gate is set to about 1.257 times the dieaway time which is at the bottom of what is a shallow valley. Thus, without going into the details of how to optimize a measurement which is traditionally quick to perform and judge by experience and trial and error, it should be clear that, if the model assumptions hold, a value of G_1 in the approximate range 0.5 to 1 times τ would be expected to be a reasonable starting point for measurement. The value of τ can be estimated reasonably well ahead of time from design calculations or from results on systems of a similar kind.

In practice an initial value for G_1 much smaller than τ is normally selected and a sequence of counts is made with the gate setting being incremented by a factor of two at each step. For instance suppose we expect the dieaway time to be of the order of 20 µs. We might use gate widths of 4, 8, 16, 32, 64, 128 and 256 µs to define a characteristic plot that can be lodged with the other records of fabrication and testing of the instrument. From these seven counts six estimates of dieaway time can be defined using Equation (5). We would expect the estimates to vary reflecting the fact that the first results emphasize short lived components while the later results emphasize longer lived components and represent an average over a longer period. For comparison to design calculations we note that the F8 coincidence tally available within the general purpose Monte Carlo N-Particle eXtended transport code (MCNPX) allows the coincidence rate to be computed for a specified predelay and gate width setting and so a direct comparison on the same grid used to acquire experimental data can be made conveniently.

We note too that the designer can often exercise considerable control over the dieaway time profile of a given instrument through the choice of moderator dimensions, the ^{3}He-gas fill pressure used in the NCC proportional counters, the use of cadmium liners, and other features while balancing the overall performance figure of merit with a complex set of other constraints. Thus, although a near perfect single exponential profile might be achievable in principle, in practice compromise design solutions are the norm and understanding and confirming the tradeoffs involved is important.

3. Illustrative Example

To illustrate how the dieaway time typically varies with increasing gate width, we report results from one representative data set acquired using the LANL Epithermal Neutron Multiplicity Counter (ENMC). The ENMC [5] is a high-efficiency (approximately 0.65 counts per fission neutron) safeguards well-counter with 121 cylindrical proportional counters of 1" (25.4 mm) diameter filled with 10 atm pressure of ^{3}He. The ^{3}He tubes are organized in 4 rings surrounding the central well. The dieaway time profile of this counter is known to be far from a single exponential. For convenience the data were acquired in list mode (because it was to be used for other purposes also), using a high-rate ^{252}Cf source (approximately 87.4 µCi) located in the center of the counter well. The strength of the source is not germane to our present discussion, but we not that we are in a domain where the accidentals coincidence rate dominates such that the traditional optimum gate width (to achieve the best precision on the doubles rate in a given assay time) would be expected to be in the vicinity of 1.2 times the effective 1/e-dieaway time. A stronger or weaker source could have been chosen for illustration, however the precision attained for a given measurement time would change. The list mode data was analyzed off line to emulate the action of a shift register. Table 1 summarizes the doubles rates extracted for a range of gate widths with fixed predelay T_p=1.5 µs. Fast accidentals sampling [6] was used to determine the contribution of accidental (or chance) coincidences since this offers better precision over event triggered sampling of the accidentals rate (although both offer the same expectation value under stable operating conditions and so either approach could be used depending on what hardware is available for data acquisition). The average total detected event rate (the singles rate) was (319365±12) counts per sec through this measurement, utterly swamping the ambient background. The measurement time was 2 hours and the data was accumulated in 720 cycles each of 10 sec duration in order to estimate the statistical precision from the scatter in the sample. The rates presented in Table 1 are dead time corrected. The dead time correction factor applied is based on the widely used empirical exponential form $\exp(\delta S_m)$ where δ is the dead time parameter and S_m is the measured (or observed) singles rate before dead time correction. The value of the dead time parameter, (0.1443±0.0128)x10^{-6} sec, was determined experimentally using a two source method (in which, in outline, two ^{252}Cf sources were measured individually and combined and the dead time was picked so that the dead time corrected combined rate was equal to the sum of the individual measurements). Since the dead time correction factor adopted does not depend on the gate width, on the measured singles rate which is constant throughout, the dieaway values derived from Equation 5 are not expected to be sensitive (at least to a high level of approximation) to the strength of the ^{252}Cf source used nor to whether dead time corrections have been applied or not.

G [μs]	D[dps]	σ [%]
4	56080	0.021
8	99825	0.019
16	162326	0.019
32	232531	0.022
64	283739	0.028
128	300334	0.040
256	301613	0.060

Table 1: Summary of doubles counting rates, D, in doubles per sec, dps, for a range of gate widths, G, obtained from ENMC list mode data. Also listed is the fractional standard deviation on the doubles rates given in %.

The doubles rates quoted in Table 1 can be used to extract corresponding dieaway times using Equation (5). The uncertainty of the calculated dieaway time values was determined based on Equation (8). Including the covariance term in Equation (8) results in a slight improvement in the estimated precision for this data set. The 1/e-dieaway time values for each gate pair are listed in Table 2 and displayed in Figure 1.

G_1 [μs]	G_2 [μs]	τ [μs]	σ [%]	ρ(D_1,D_2)	σ incl. covariance [%]
4	8	16.10	0.016	0.125	0.015
8	16	17.09	0.009	0.373	0.007
16	32	19.09	0.006	0.401	0.005
32	64	21.15	0.006	0.094	0.006
64	128	22.54	0.014	0.242	0.012
128	256	23.45	0.133	0.137	0.124

Table 2: Summary of 1/e-dieaway times extracted from the doubles counting rates listed in Table 1. The fractional standard deviations reported in column 4 assume there is no covariance between the pair of counts. The corresponding correlation coefficients are listed in column 5. In column 6 the reduction of the uncertainty due to covariance term can be seen.

The dieaway time values in Table 2 exhibit an increasing trend with increasing gate width. As discussed in the previous section, this trend reflects the short and long lived components of the neutron dieaway time in the counter. The data maps out the variation in the effective dieaway parameter over a broad temporal range. To better illustrate this trend, Figure 1 shows the dieaway time as a function of gate pair average. The error bars, including the covariance term, are smaller than the size of symbols. The variation of the measured dieaway time with gate width is a demonstration that the dieaway time of this counter is far from a single exponential.

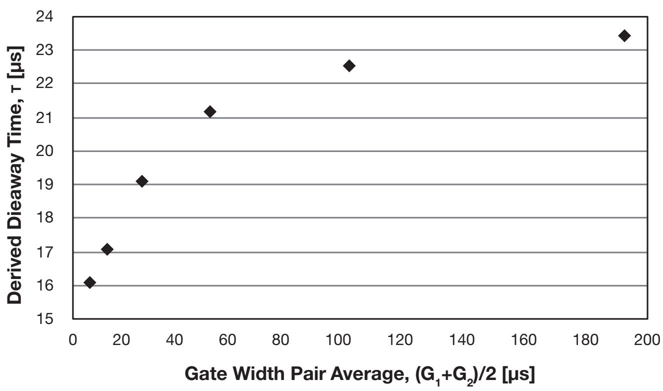

Figure 1: Plot of the 1/e-dieaway time extracted for a series of gates of different width as a function of the average width of each gate pair. This illustrate that in truth the detector has several time components.

4. Conclusions

We have shown how the effective 1/e neutron capture dieaway time inside the detector head, which describes the time profile of detection of one neutron relative to correlated neutron which serves as a trigger, may be conveniently estimated using just two well chosen coincidence gates differing in width by a factor of two. This approach has been used at LANL for a number of years as a way to characterize detection systems and confirm design predictions. The new feature of this work is the derivation of the influence of the counting precision on the extracted value of the dieaway time, which is important in order to compare different measurements made on the same counter at different times during its operational life for quality assurance purposes. In addition, we illustrate that real detector systems do not exhibit perfect exponential behavior, described by a single 1/e-time constant, over the whole dynamic time-range following a trigger; an aspect that can be investigated by varying the gate widths G_1 and G_2. When list mode data acquisition is used and the various doubles rates are obtained by analyzing a single pulse train in software then the rates are correlated and the possibility of non-zero covariance must be considered according to the approach developed here. The shift register analysis based approach presented, although approximate, because it does not lend itself to extracting multiple time components according to a single continuous curve (as might be generated by time interval analysis methods applied to list mode data), has the virtue of being easy to implement and explain in a test procedure. The practice will also continue as it provides a link to historical test procedure records. Given that real systems do not behave in an ideal way the results obtained can serve to characterize each system in a general way and allow families of detectors to be compared to ensure consistency of production. Results can also be generated periodically once an instrument has entered into service as part of the state of health monitoring undertaken within the quality assurance program. Because the effective 1/e-dieaway time is not explicitly used during data analysis to produce an assay result the measurement need only provide an adequate descriptive characteristic, not a calibration parameter. The exception is that some dead time correction formulations may use the dieaway time as a parameter, but the combination of the dead time and the dieaway time needed for dead time corrections are best treated as effective or empirical constants, in this case, chosen to generate corrections of acceptable quality over a given operational range. This is because the mathematical derivations of dead time loss are founded on simplifying assumptions which actual systems only approximate.

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Reactor Neutrino Detection for Non Proliferation with the NUCIFER Experiment

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Abstract:

Neutrinos are the most abundant matter particles in the Universe. Thoroughly investigated in basic science, the neutrino field is now delivering first applications to the monitoring of nuclear reactors. The neutrinos are emitted in the decay chain of the fission products; therefore measuring their flux provides real-time information, directly related to the fission process occurring in the reactor core. Because of the very weak interaction of neutrinos with matter a neutrino detector can stand outside the core containment vessel and provide a non-intrusive and inherently tamper resistant measurement.

After a brief review of the existing data and worldwide projects, we present the NUCIFER experiment. The active part of the detector is a tank filled up with one ton of Gadolinium-doped liquid scintillator. Sixteen photomultiplier tubes, isolated from the liquid by an acrylic buffer, read out the light produced by the interaction of a neutrino with the protons of the liquid. The tank is surrounded by plastic scintillator plates to veto the cosmic rays. Then polyethylene and lead shielding suppress the background coming from external neutrons and gamma rays respectively.

The NUCIFER detector has been designed for an optimal compromise between the detection performances and the specifications of operation in a safeguards regime. Its global footprint is 2.8 m x 2.8 m and it can monitor remotely the nuclear power plant thermal power and Plutonium content with very little maintenance on years scale. The experiment is currently installed near the OSIRIS research reactor (70 MWth) at CEA, in Saclay, France. First data are expected by May 2012.

This work is done in contact with the IAEA/SGTN division that is currently investigating the potentiality of neutrinos as a novel safeguards tool. A dedicated working group has been created in 2010 to coordinate the simulation effort of various reactor types as well as the development of dedicated detectors and define and eventually test the end product to be used by the agency.

Keywords: *neutrino; non-proliferation; safeguards; remote monitoring; reactor*

1. Introduction

Neutrinos are largely produced in reactor cores by β-decay of neutron rich fission products (FPs) from U and Pu into more stable nuclei: ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{-} + \bar{\nu}_e$. Nuclear reactor power comes from the energy produced both during the fissions and the β-decays. This second contribution is about the 7% of the total amount of produced power and it is called decay heat. The global released energy per fission is about 200 MeV with the emission of six antineutrinos. This means that the flux emitted by a one GW_{th} reactor is ~1.5 10^{20} antineutrinos/second. This huge emitted flux allows us to detect their signal with a relatively small detector (1 ton scale) placed a few tens of meter from the core even if the interaction cross section between matter and neutrinos is very tiny (~10^{-43} cm^2).

The FPs' mass distribution depends on the fissioning isotopes (^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu) and incident neutron energy. The mean energy released per fission, the mean number of neutrinos emitted by FP beta decays and their mean energy are different depending on the initial fissioning isotope. So the detection of these neutrinos would give a remote and real time image of the core composition.

In section 2 we will present the principle of reactor monitoring by neutrino detection and the world effort on this subject. In section 3 we will present our detector prototype, Nucifer, while in section 4 we will report on its expected performances.

2. Reactor monitoring by antineutrinos

2.1. The principle

Reactor antineutrinos are usually detected by using large volumes (tens of tons) of liquid scintillator (hydrocarbon) doped with Gadolinium (Gd). The detection reaction is the inverse β-decay $\bar{\nu}_e + p \rightarrow e^{+} + n$, which is the reaction with the largest cross section for few MeV neutrino interaction. The e^+ detection produces a prompt signal of energy $E_{prompt} = E_{\bar{\nu}_e} - (M_n - M_p) + m_e$, with M_n the neutron mass, M_p the proton mass, m_e the positron mass and $E_{\bar{\nu}_e}$ the neutrino energy. This first pulse is followed by a delayed (τ ~ 30 μs) signal induced by the radiative capture of the neutron on Gd with the emission of a gamma cascade of total energy ~8 MeV. The mass excess of the final state of the inverse β reaction implies a kinematical threshold of $(M_n - M_p + m_e)c^2 = 1.8$ MeV for the incident antineutrino energy. If we consider the reactor antineutrino flux above this threshold, the reaction cross section and the number of proton target for a typical scintillator chemical formula (for example 80% $C_{12}H_{24}$ and 20% of $C_{16}H_{18}$) the number of antineutrino interactions in a target of mass M_{tg} [tons] placed at a distance D [m] from a reactor of thermal power P_{th} [GW] can be calculated as $N_{int}/day \approx 1.0\ 10^6 \times P_{th} \times M_{tg}/D^2$. About 4600 interactions/day can be expected in a 1 ton target placed at 25 m from a 2.9 GW_{th} power reactor (i.e. 1 GW_{el} assuming 35% thermal efficiency), which means a 1% of statistical error within few days of data taking. This is a quite remarkable result for this detector size, which is considerer small for neutrino experiment scale.

Fission parameters	^{235}U	^{239}Pu
E/fission[a] (MeV)	193.5	198.9
<Eν> above threshold (MeV)	2.94	2.84
Nν/fission above threshold	1.92	1.45
$<\nu_{int}>$ (10^{-43} cm^2)	3.20	2.76

[a] Only the energy contributing to the thermal power is quoted here (i.e. total released energy minus antineutrino energy)

Table 1: Relevant fission parameters of 235U and 239Pu.

The two main fissile isotopes contained in the fuel of common commercial reactors (pressurized water reactor or PWR) are ^{235}U and ^{239}Pu. Fresh Uranium fuel is typically enriched at 3.5% in ^{235}U, while ^{239}Pu is produced by neutron captures on the original ^{238}U followed by two consecutive β-decays: $^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$. During a reactor cycle ^{235}U is burned while ^{239}Pu is produced. This means that the relative contribution to the total number of fissions induced by these two isotopes changes over time: it increases for the ^{239}Pu while decreases for the ^{235}U. This effect is called "burn-up".

Because the FPs of these two isotopes have different atomic masses their β-decays result in different neutrino fluxes. The idea of a neutrino probe to monitor the reactor fuel composition is based on the capability to discriminate between different generated fluxes.

Considering the key parameters for ^{235}U and ^{239}Pu fissions summarized in table 1, we can calculate the ratio of detected antineutrinos in the two extreme cases, where all fissions come from pure ^{235}U or pure ^{239}Pu to produce the same thermal power:

$$\frac{N_\nu^U}{N_\nu^{Pu}} = \frac{\left(\frac{N_\nu}{fission} \times \sigma\right)^U \left(\frac{E}{fission}\right)^{Pu}}{\left(\frac{N_\nu}{fission} \times \sigma\right)^{Pu} \left(\frac{E}{fission}\right)^{U}} \approx 1.6$$

This large difference suggests the possibility to use the antineutrino rate to monitor changes in the relative amounts of ^{235}U and ^{239}Pu in the core.

Reactor fuel composition monitoring through neutrino detection can be done both by performing absolute flux measurement during reactor cycle or relative flux measurements before and after a reactor stop. In the fist case the monitoring method can be obtained from the declaration of the power history of the operator: the expected time evolution of the neutrino flux can be predicted and compared with the data. This controls the correct operation of the reactor over the course of the cycle [1]. The second neutrino detection monitoring method relies on relative antineutrino flux measurements made before and after a given period of time (suspicious reactor stop, refuelling, ...). A neutrino flux change can be induced both by a change in the core composition or by a change in the produced thermal power. Assuming an independent knowledge of thermal power, the comparison between two relative neutrino flux measurements would allow us to calculate the relative change in U/Pu composition of the core. The big advantage of making relative measurements is that all normalization errors (solid angle, detection efficiency, …) cancel out.

2.2. World effort

The idea of applying neutrino to reactor remote control was firstly presented to the International Atomic Energy Agency (IAEA), the United Nations agency in charge of the development of peaceful use of atomic energy, in 2003. The IAEA asked for a feasibility study to determine whether antineutrino detection methods could provide practical safeguard tools for selected applications. This encouraged the international community to work on prototype design and performance studies. Two other meetings about the subject where held at the AIEA in October 2008 [2] and October 2010 [3]. Results by pioneering experiments like the SONGS1 detector [4], new projects like NUCIFER and prediction of non-proliferation monitoring scenario coming from the accurate simulation of different reactor types [5][6][7][8] were presented. During the 2010 meeting the AIEA has created a dedicated working group on this last research developments [9]. A first meeting of this working group was organized in September 2011 [10]. The draft of a summary and prospect document is in progress.

This interest from the AIEA motivated the international scientific community to search for solutions to install a neutrino detector close to a nuclear reactor. The requirement is to build a relatively small neutrino detector, remote controlled, safe and easy to operate by non-experts. One of the main challenge is to operate a detector located close to the Earth surface. Neutrinos are weakly interacting particles and close to the Earth surface their signal can be easily mimicked by the cosmic ray induced signal. Typically, neutrino detectors are best placed in deep underground laboratories to avoid this problem. The non-proliferation specific requirement of compactness implies to be close to the reactor and quasi on Earth surface. The main challenge is, then, the neutrino signal extraction from the background induced by cosmic rays.

The pioneer experiment in the field of antineutrino detection for reactor monitoring was performed in 1986 at the 1.3 GW_{th} Rovno reactor in Russia [11]. The detector was a $1m^3$ plexiglass tank filled with Gd-doped liquid scintillator and surrounded by 84 photomultipliers, placed at about 18 m from the reactor core. With a daily detection rate of the order of a thousand events they were able to clearly see a ~6% burn-up effect on neutrino flux over a reactor cycle and to measure the proportionality law between neutrino rate and thermal power [12].

Other results demonstrating the possibility of monitoring the antineutrino flux from nuclear reactors in correlation with burn-up effect and refuelling have been shown by the SONGS1 experiment developed by the Lawrence Livermore National Laboratory in the US. The target was 0.64 tons of Gd doped liquid scintillator and the detector was placed at 25 m from the core of the 3.46 GW_{th} San Onofre Nuclear Generating Station (SONGS), California. With a typical number of ~400 detected neutrinos per day, this experiment measured the burn up effect over two reactor cycles (about 18 months) and a ~10% variation in rate due to the replacement of burnt fuel containing 250 kg of ^{239}Pu by fresh fuel containing 1.5 tons of ^{235}U [4] [13].

These two detectors were placed at small shallow depth and they had some natural shielding to cosmic rays. Prospects of future deployment closer to surface have triggered the study of different techniques to improve background rejection: standard doped liquid scintillator detectors like Nucifer in France or Kaska in Japan, Gd doped water at Angra in Brazil and organic scintillators layed with high neutron cross section materials at the LLNL in the US, in Russia, in the UK, in Italy or Japan, or even new detection techniques like coherent antineutrino-nucleus scattering in Taiwan and in the US [9] [14] [15].

3. Nucifer experiment

3.1. Detector design

The Nucifer concept has been developed by following the IAEA requirements, the necessity of a good detection efficiency and a large background suppression. This last point is the real challenge for this detector since it will be placed close to the Earth surface, where the cosmic ray induced background (muons and induced secondaries such as neutrons) becomes really important (typical sea level rate is 1 muons per minutes per cm^2 [16]) .

The detector design has been realized in collaboration by the CEA/IRFU/Spp and SPhN of Saclay and the CNRS/IN2P3/Subatech laboratory. The design was optimized using a dedicated GEANT4 [17] simulation of the detector response to signal and background and by performing several background measurements at the Osiris (CEA-Saclay) and ILL (Grenoble) research reactors where the detector will be first tested.

The two main background sources are cosmic muons (and induced particles like fast neutrons) and gammas generated by the reactor, since the detector will be placed a few meters away from the core. The first type of background can give rise to a correlated signal (proton recoil from neutron scattering which can mimics the positron prompt signal plus correlated neutron capture to reproduce the delayed signal), while the second type of background contributes to the accidental signal (gamma detection which mimic the prompt signal plus accidental neutron capture). The gamma spectrum and flux at the two research reactors have been measured and simulated for the Osiris reactor [18]. The maximum gamma energy is around 10 MeV.

The optimised detector is composed of a neutrino target detector, an active muon veto to tag the muon induced background and neutron and gamma shielding. The global view of Nucifer is reported in figure 1, while the target detector and one module of the muon veto are shown separately in figure 2.

The neutrino target detector is a steel cylindrical tank (height 1.8 m, diameter 1.2 m) with internal surface coated with white Teflon to insure compatibility with the scintillator liquid and to increase light diffusion. The tank is filled with about 0.85 m3 of Gd-doped liquid scintillator. A 25 cm thick acrylic disk optically couples the PMTs with the liquid surface while shielding the intrinsic PMT radioactivity from the scintillator and ensuring a more uniform response in the whole target volume. Sixteen large PMTs (8 inches diameter) located at the top of the detector vessel ensure an efficient light collection. PMTs are kept in an inert Nitrogen atmosphere inside the vessel to reduce fire hazard. A LED based light injection system allows us to monitor the PMT gain and possible instrumental drifts. In addition small radioactive sources can be deployed along the target central axis inside a vertical tube.

Two hermetic layers of shielding protect the detector from gamma and neutron backgrounds. Starting from the outer layer we can find a 10 cm Pb layer and a 14 cm Polyethylene layer. An extra wall of 10 cm of lead is place between the experiment and reactor pool wall in the core direction.

The muon veto detector is placed between the shielding and the neutrino target as shown in figure 1. This is mandatory in order to protect the veto from the high energy gamma flux coming from the reactor core. The veto will surround 5/6th of the neutrino target. It is based on a novel concept: thirty tone modular detectors, each one containing a 5 cm thick plastic scintillator of 150 to 170 cm length and 25 cm large. The scintillator is read by one PMT decoupled from its surface. The scintillator thickness has been chosen in order to discriminate cosmic muons from gamma background. Since cosmic ray muons are generally high-energy particles, we can assume that they are minimum ionizing particles. For plastic scintillator, the minimum ionizing value of dE/dx is ≈ 1.9 MeV.cm^{-2}. Therefore a 5 cm plastic slabs lead to have an averaged deposited energy of about 10 MeV. This energy is bigger than natural gamma background which have energies lower that about 3 MeV and at the upper limit of Osiris gamma spectrum. We can, then, discriminate muons from gamma background by applying an opportune threshold on the detected energy. Since the detected energy derive from the deposited one through the light collection, this threshold also depends on the light collection uniformity. The choice of one PMT per module has been made to reduce costs, but this clearly reduces the uniformity of module response to light collection. To optimise the module geometry and PMT positioning for maximal uniformity response and to study the detector performance we developed two simulations based on GEANT4 and Litrani [19] codes. The final measured detection non-uniformity is less than a factor 2.5 (i.e. the same energy deposited in the less efficient end most efficient position for light collection induce a maximal change of a factor 2.5 in the detected energy measurement). The threshold of each module has been set to minimize the gamma detection while maximizing the muon detection efficiency to be greater than 95%. Energy threshold calibration and detector performance has been studied by performing several measurements on one prototype module: muon signal detection, measures with gamma sources (gamma prompt from AmBe, ^{60}Co) and a campaign of measurements at the Osiris reactor where the detector has been placed. The final estimated threshold in energy is between 2 MeV and 5 MeV depending on the event position inside the scintillator.

The overall footprint, including shielding and veto detector, is about 2.8 × 2.8 m^2. Such a compact target is relatively small, safe and will ensure high detection efficiency. The

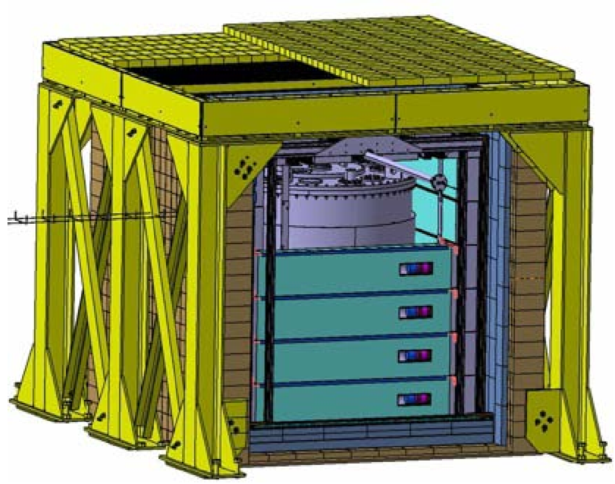

Figure 1: Design of the NUCIFER detector contained in the shielding and muon-veto.

neutrino detection efficiency is limited by the detection efficiency of the prompt e$^+$ and of the delayed radiative capture on Gd of neutrons generated by the inverse β-decay reaction. From simulations, this efficiency results ~50% when we apply a threshold of 2 MeV on the e$^+$ detected energy and of 4 MeV on the gamma cascade detected energy.

3.2. Road-map

The NUCIFER detector with its neutrino target, muon veto and shielding have been installed at 7 m from the core of the Osiris research reactor at the CEA of Saclay. Osiris is a 70 MWth reactor and the detector is placed at a depth of 5 meter water equivalent (m.w.e.). The data taking will start in May 2012 for about one year to test the NUCIFER response to reactor neutrino. The detected neutrino rate during reactor ON periods at nominal power will be of about 650 neutrinos/day. Regular reactor OFF periods (10 days after each 20 days cycle) will allow studying the spectrum of cosmic background and the efficiency of its rejection.

Figure 2: Left: design of neutrino target detector. Right: interior of one module of the muon veto

A further step will be to deploy NUCIFER close to a commercial nuclear reactor, possibly in a country under Safeguards to finally demonstrate the potential of the NUCIFER concept, possibly in collaboration with the IAEA.

4. Nucifer performance

4.1. Neutrino target calibration

For tests, the neutrino target detector has been filled by unloaded liquid scintillator composed of linear alkyl benzene (LAB) with PPO (2 g/l) and bis-MSB (20 mg/l) at the end of 2009. In 2010 its performance have been studied and the energy calibration performed by using some sources (Americium-Berylium, Cesium 137, Cobalt 60 and Sodium 22) inserted in the centre of the active volume by the Teflon coated stainless steel calibration tube. The measured and simulated calibration curves are displayed in figure 3 and show an excellent agreement, within a few percent between 667 keV and 5.5 MeV.

By using an Am-Be radioactive source emitting neutrons in coincidence with 4.4 MeV gammas, with a rate of 90 Bq, we were able to mimic the neutrino signal consisting in two correlated pulses within few 100μs. Figure 4, left, shows the distribution of the delay time between the prompt 4.4 MeV gamma and the delayed neutron candidates. Experimental data have been fitted with a sum of an exponential and a constant, the first component, with a 209 μs time constant, clearly attests the neutron capture on hydrogen, and the second is consistent with the expected accidental background of our detector (naked vessel without shielding). Figure 4, right, shows the energy spectrum measured (black curve) from this source compared with the simulated one (red curve). The right bump shows the sum of prompt energies deposited by the gammas and the neutron induced recoiling protons. The peak on the left

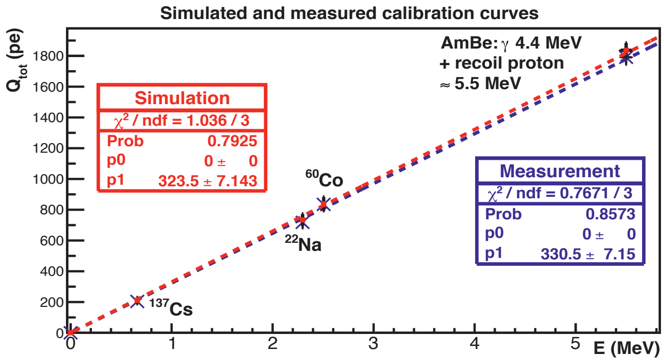

Figure 3: Results of the energy calibration through different gamma ray and neutron sources in the unshielded NUCIFER detector (blue) compared with the simulation (red).

corresponds to the 2.2 MeV gamma emitted by neutron capture on Hydrogen. Both prompt and delayed signals, which are similar to the ones expected in case of neutrino detection, are well reproduced by the simulation.

4.2. Background rejection

Montecarlo simulations indicate that the 10 cm lead shielding placed all around the target plus the 10 cm lead wall placed toward the core direction are enough to assure a signal to background ration of 1 for accidental background. The main source of background in Nucifer is, then, the correlated one caused by fast neutrons induced by cosmic ray muons. We studied the possibility of using the pulse shape discrimination (PSD) to disentangle the neutrino signal from these neutrons, in the case they are not tagged by the veto detector. This method is based on the fact that a proton recoil (prompt signal of correlated background) in the final Gd doped liquid scintillator of Nucifer (Eljen-EJ335-05) gives origin to a signal with a shape different from the one induced

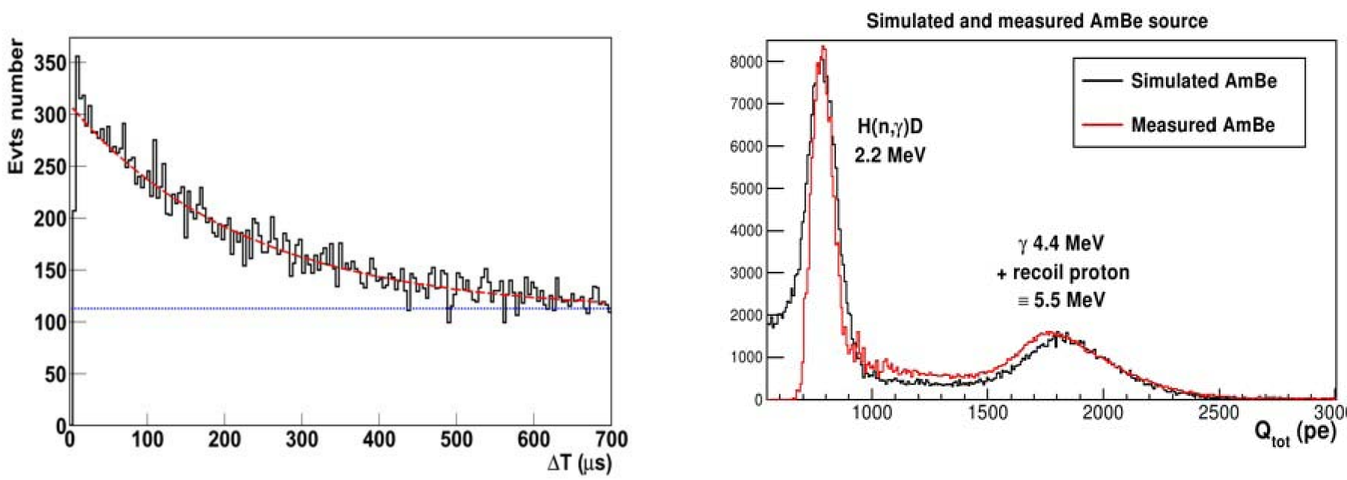

Figure 4: Results of neutron calibration of the unshielded NUCIFER detector using an Am-Be radioactive source. Left: the plot displays the time delay between the prompt 4.4 MeV gamma ray and candidates of a neutron capture. A clear exponential decay with a 209 μs time constant (red dashed curve) appears on top of the flat uncorrelated background (blue dotted line), attesting for the neutron capture signal in our unloaded liquid scintillator (LAB). Right: measured energy spectrum (black curve) is compared the simulated one (red curve)

by a positron (prompt of neutrino signal). This is due to the longer decay time of scintillator for particles with higher dE/dx which translate into a longer tail in the final signal.

The PSD capability of the Nucifer liquid scintillator as measured on a dedicated bench (100 cm^3 liquid cells) is shown in figure 5: by plotting the charge contained in the tail of the signal as a function of its total charge we can clearly identify two different zones for proton recoil and positron signals.

The final performance of the PSD will be affected by the volume effect of the Nucifer target. Complementary measurements using the Am-Be source give an indication for a 90% efficiency for proton recoil rejection in the final NUCIFER configuration [20]. In this condition the expected signal to correlated background ratio is 2.5.

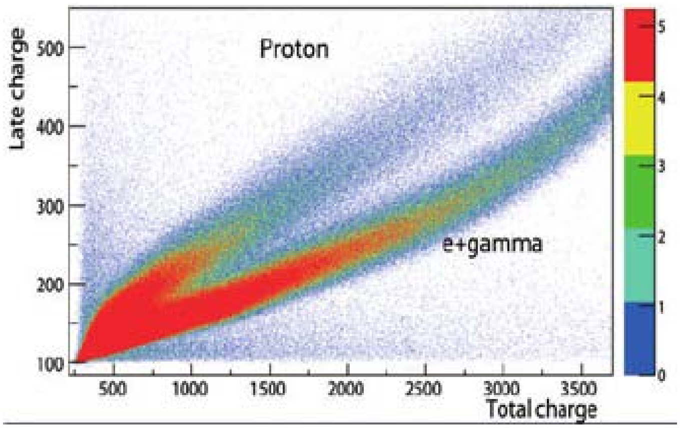

Figure 5: Result of PSD test on the Gd doped liquid scintillator of Nucifer: plot of the charge contained in the tail of the signal as a function of its total charge. We can clearly identify the two different zones for proton recoil and positron signals. Expected detection threshold is around 1500 on horizontal axis.

4.3. Remote control

Among the IAEA specifications there is the request of a remote controlled, simply to be used detector.

We worked on a remotely controlled acquisition system, PMT high voltage setting and monitoring, run start and slow control. The data output and possible alarms can be also monitored on-line by a comprehensive display.

The detector stability and linearity are monitored at the 1% level using four independent LEDs.

5. Conclusions

The NUCIFER neutrino experiment aims at demonstrating the possibility of high accuracy, reliable, and temper-proof monitoring of fission nuclear reactor thermal power and detecting undeclared Plutonium retrieval. The detector has been tested in an almost final configuration and calibration preliminary results indicate a good understanding of the detector time and energy responses. This attests for the readiness of NUCIFER for the reactor antineutrino hunt. The detector has been integrated at the OSIRIS research reactor at CEA-Saclay during the last months and will start to collect data in May 2012.

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Verification of the enrichment of fresh VVER-440 fuel assemblies at NPP Paks

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Abstract:
A Non Destructive Analysis (NDA) method was developed for the verification of ^{235}U enrichment of both homogeneous and profiled VVER-440 reactor fresh fuel assemblies by means of gamma spectrometry. A total of ca. 30 assemblies were tested, five of which were homogeneous, with ^{235}U enrichment in the range 1,6% to 3,6%, while the others were profiled with pins of 3,3% to 4,4% enrichment. Two types of gamma detectors were used for the test measurements: 2 coaxial HPGe detectors and a miniature CdZnTe (CZT) detector fitting into the central tube of the assemblies. It was therefore possible to obtain information from both the inside and the outside of the assemblies.

It was shown that it is possible to distinguish between different types of assemblies within a reasonable measurement time (about 1000 sec). For the HPGe measurements the assemblies had to be lifted out from their storage rack, while for the CZT detector measurements the assemblies could be left at their storage position, as it was shown that the neighbouring assemblies do not affect measurement inside the assemblies' central tube. The measured values were compared to Monte Carlo simulations carried out using the MCNP code, and a recommendation for the optimal approach to verify the ^{235}U enrichment of fresh VVER-440 reactor fuel assemblies is suggested.

Keywords: fresh fuel assemblies; U-235 enrichment; HRGS/MRGS

1. Scope

At Paks NPP the necessity of checking the enrichment of the fresh fuel assemblies was raised as a means to further guarantee the safe operation of the plant as requested by IAEA and EURATOM. Due to the high number of assemblies produced, it is advisable to double-check that the enrichment of the shipped assemblies corresponds to the declared values. If a deviation from the declared value is revealed during reactor operation only, the shutdown of the reactor and dismounting and refuelling the core may cause interruptions in the power production and involve high expenses.

2. Experimental[1]

The gamma spectra were measured using two types of detector systems. High resolution spectra were taken by a coaxial high purity HPGe detector placed at a distance of 35 cm normal to the middle hight of one side of an assembly (Fig 1). CZT detectors were used to take the spectra in the central hole of the assembly (Fig 2).

Fig. 1: HPGe Detector stand and assembly in measuring position

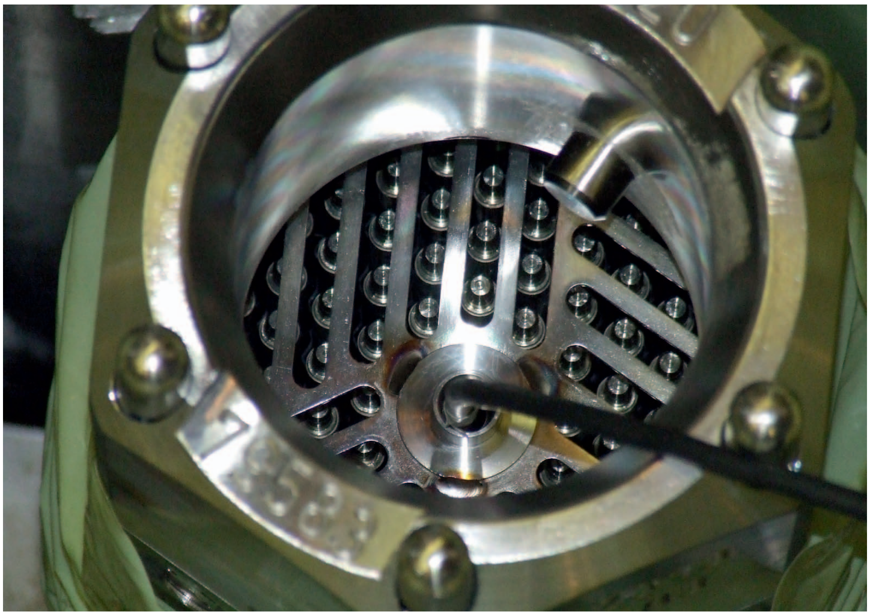

Fig. 2: CZT detector in the central hole of the assembly

Using two detectors was necessary because the profiled assemblies had to be characterised from both inside and outside. Two types of assemblies are used at Paks NPP: homogeneous ones with an enrichment of 1.6, 2.4 and 3.6%, and profiled ones with 3.8 and 4.2% nominal enrichment. The maps of enrichment of the pins in the profiled assemblies are shown on Figs 3 and 4 resp.

For calibration, spectra measured on the homogeneous assemblies were used. As a consequence of the inhomogeneous enrichments in the profiled assemblies different results are expected in the case of different layouts (Figs 1, 2).

Preliminary experiments were carried out by a planar HPGe detector to determine the enrichment of the fresh fuel assemblies (FFAs). The enrichment was determined using the uranium gamma spectrum in the 90 – 100 keV region by using the MGAU[2][3] code. Results were obtained in agreement with the nominal enrichments in the case of homogeneous assemblies. Due to self-absorption, the lower energy gamma-rays arrive at the detector from the outer pins of the assemblies looking to the detector's direction, whereas the contribution of the gamma-rays emitted by the inner pins is smaller.

For HPGe coaxial detector measurements, the enrichment was determined on the basis of the intensity ratio of 186 keV (^{235}U) to 1001 keV (^{234m}Pa) peaks. The activity of the latter reaches its radioactive equilibrium with that of ^{238}U already 3 months after the enrichment. Absolute enrichment cannot be calculated, however, because the ratio depends considerably on the position of the detector. Also, the attenuation of the two peaks differs substantially since their energy

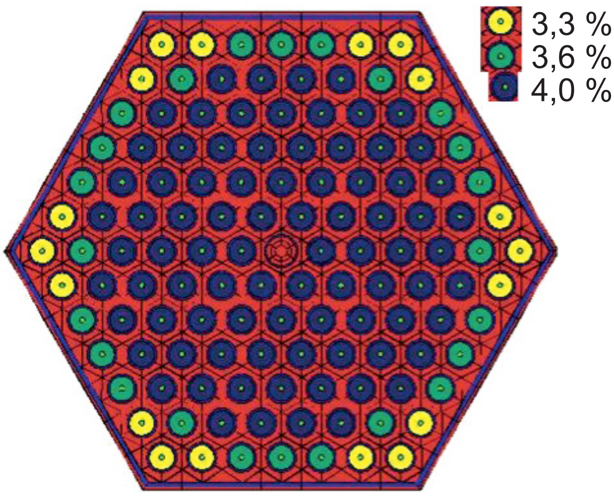

Fig. 3: Schematic diagram of the 3.8% profiled assembly

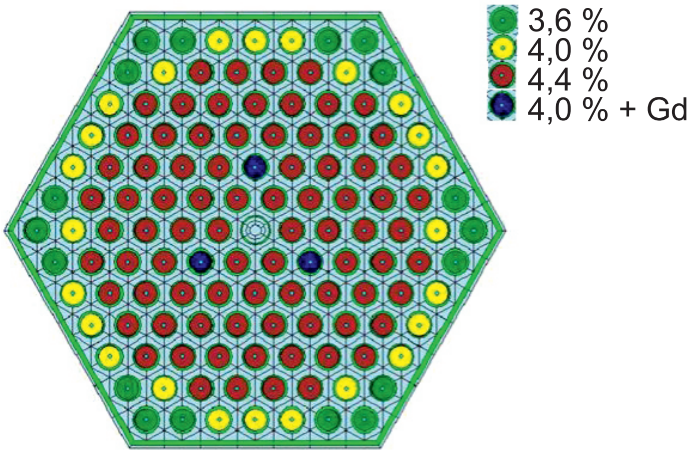

Fig. 4: Schematic diagram of the 4.2% profiled assembly

differs. Therefore, this method can be used for enrichment determination after calibration by standard assemblies and for stable geometries only. Owing to the higher penetrability of the 186 keV energy gamma–rays as compared to those at about 100 keV, the method can be used to gather information on pins in the inner parts of the assemblies. Nevertheless, the 'insight' into the assemblies is limited to a few rows' depth only. Since the geometry can be kept very stable and the amount of ^{238}U is nearly the same, it may be more practical to measure the 186 keV peak area instead of measuring peak area ratios 186 keV/1001 keV.

The HPGe detector was placed at a 35cm distance to the assembly at the half height normal to the face of the assembly. No collimator was used, thus the whole assembly was 'visible' to the detector. The use of a CZT detector placed into the central tube of the assembly complements the measurement from the outside by determining the 186 keV gamma spectrum emitted by the inner pins. Because of the size of the detector,186 keV photons are identified well, while 1001 keV photons are detected inefficiently.

Because of the self-absorption of uranium in the assembly, the 186 keV gamma peak detected originates from the pins in a few circles around the central tube, whereas the contribution of the pins situated farther outwards is negligible.

The enrichment of the assemblies was verified as follows:

1. Spectra of assemblies of homogeneous composition were taken by the smaller Ge detector and calculated based on the MGAU code in order to check whether the measured values comply with the declared ones (1.6, 2.4, 3.6 %). These assemblies were used as standards for calibration.

2. The spectra of the assemblies assigned as standards were taken by the larger Ge detector fixed on the inspection stand. It was not necessary to use a collimator, because the presence of other fuel assemblies did not disturb the measurements. The background spectrum was taken as well, and this was repeated whenever the number and position of the assemblies in the stand changed significantly. Spectra of the assemblies to be examined were also taken. The detector was put in a stable position at middle-height of the assemblies, at a distance of about 35 cm (see Fig. 1). At this distance the measurement uncertainty of the 186 keV peak area drops below 0.5% during a 500 s measurement time. The width of a face of the assembly is 83.7 mm.

3. Spectra of the standard assemblies and of those to be examined were taken by the CZT detector placed in the central tube at a defined depth (see Fig. 2). The necessary measurement time of the detector is 2000 s for reaching an uncertainty of 1% of the peak area.

3. Results and evaluation

Count rate values of the 186 keV peak areas of the standard assemblies were plotted as a function of the enrichment. A straight line was fitted to the points in order to determine the line parameters. The 186 keV count rates of the assemblies examined show the average enrichment of 'visible' pins. The calculations have been performed for the measurements carried out both by the HPGe and the CZT detector.

The particular pins gave different contributions to the result due to the different absorption by other pins. The measurement setup has been modelled based on the MCNP code. Two cells modelling the detectors were applied, one of them in front of one face of the assembly filled by HPGe, the other one in the centre of the central tube representing the CZT. The results from the tallies of the former are referred to as 'outside', those of the latter as 'inside' in Table 1. Results of the runs are to be compared with the enrichment values calculated from the measurements. The data series from model and from measurement should agree within the measurement uncertainties.

Measurements have been carried out and results have been obtained so far for 10% of the 3 fresh fuel shipments arrived since the preliminary measurements. The tests were carried out in the fresh fuel storages (FFS) 1 and 2 of Paks NPP. The equipment was calibrated on the available standard homogenous assemblies of different enrichment in every experiment (3, in some cases 2). Ca. 30 assemblies of 4.2% nominal enrichment and an additional few of 3.8% nominal enrichment arrived earlier were checked. The spectra were acquired for 1000s and 2000s for Ge detectors and the CZT respectively. To determine the reproducibility of the method, in some cases all six sides of the assemblies were measured by the larger Ge detector. Plots of the results of the individual measurements are shown in Figs 5 and 6 for Ge and CZT detectors resp. Error bars are grouped according to the measurement series. These plots verify that our method makes a clear distinction between the assemblies of 3.8 and 4.2% nominal enrichment. In Table 1, measured and calculated values are compared, The measured values correspond to those predicted by MCNP calculations, and the nominal value lies between the measured and calculated values from 'inside' and 'outside'.

Note that the 3.6% homogeneous and the 3.8% profiled type assemblies give same counts at 186 keV peak because of the weighted average of different enriched pins by HPGe measurements. The CZT detector's measurements tell the two types of assembly apart.

4. Summary

The enrichment of both the 'inside' and 'outside' of fuel assemblies was determined by evaluating the gamma spectra measured with HPGe and CZT detectors. The measured values agreed with the values calculated based on the MCNP code, which shows that this measuring method

Assembly type	Nominal Enrichment	MCNP Calculated (inside)	CZT Measured enrichment Central hole	Measurement Uncertainty (2σ)	MCNP Calculated (outside)	HpGe Measured enrichment, (outside)	Measurement Uncertainty (2σ)
Homog. Standard	1.6		1.59			1.61	
Homog. Standard	2.4		2.41			2.39	
Homog. Standard	3.6		3.60			3.60	
Profiled	3.8 Avg	4.00	3.97	0.06	3.55	3.60	0.05
Profiled Series 1	4.2 Avg.	4.34	4.33	0.13	3.91	3.94	0.06
Profiled Series 2	4.2 Avg	4.34	4.34	0.07	3.91	3.91	0.04
Profiled Series 3	4.2 Avg.	4.34	4.31	0.06	3.91	3.89	0.03

Table 1: Examined assemblies

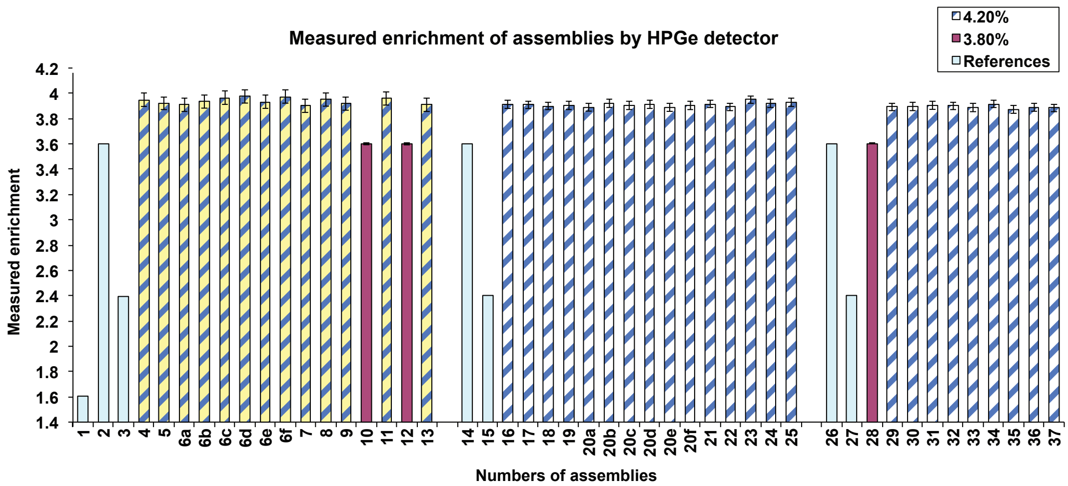

Fig. 5: Enrichment of the fuel assemblies measured by HPGe detector

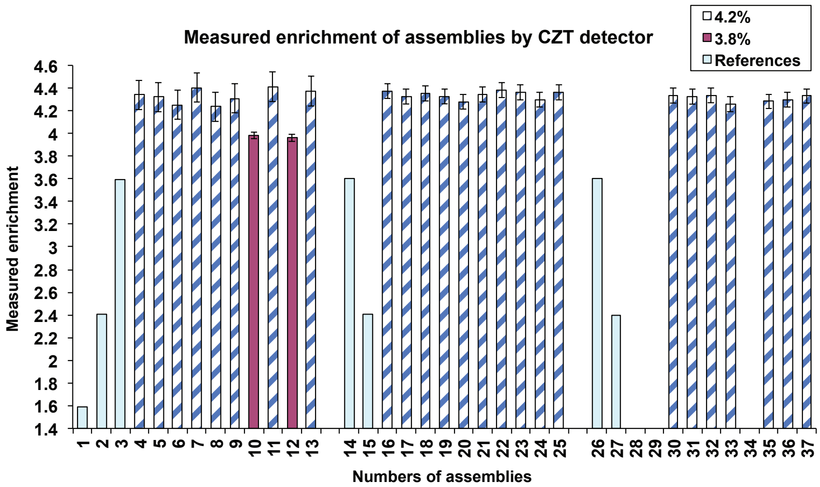

Fig. 6: Enrichment of the fuel assemblies measured with a CZT detector

is a viable means to double-check whether the enrichment values of assemblies corresponds to the declared values.

The margins of error of this method and the limits of its application are to be determined by MCNP simulations taking into account the measurement uncertainties. It remains to be examined whether divergences in the enrichment of single pins of the assembly can be detected by this method, and whether the position of pins with gadolinium can be spotted. For practical reasons the total amount of time at Paks NPP is limited, therefore another task is to determine how much measurement time can be reduced while keeping measurement uncertainties at an acceptable level. The ideal solution of this dilemma would be of course to design and produce a geometry of CZT detectors combining good resolution, small size, short measurement times and low margins of error.

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Filtering with the Centered Moving Median to Effectively Monitor Solution Processes for Safeguard Purposes

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Abstract:

Reprocessing plants require continuous and integrated safeguards activities by inspectors of the IAEA and Euratom because of their proliferation-sensitivity as complex facilities handling large quantities of direct use nuclear material. In support of both organizations, the JRC has developed a solution monitoring software package (DAI, Data Analysis and Interpretation) which has been implemented in the main commercial European reprocessing plants and which allows enhanced monitoring of nuclear materials in the processed solutions. This tool treats data acquired from different sensor types (e.g. from pressure transducers monitoring the solution levels in tanks). Collected signals are often noisy because of the instrumentation itself and/or because of ambient and operational conditions (e.g. pumps, ventilation systems or electromagnetic interferences) and therefore require filtering. Filtering means reduction of information and has to be applied correctly to avoid misinterpretation of the process steps. This paper describes the study of some filters one of which is the centered moving median which has been revealed as a powerful tool for solution monitoring.

Keywords: solution monitoring; safeguard; reprocessing; filter; median

1. Introduction:

In spent fuel reprocessing facilities, some nuclear material (NM, mainly U and Pu) is present in considerable amounts in liquid or powder form. The reprocessing plants combine different characteristics which make them particularly “challenging” for safeguards activities. The shearing of spent fuel assemblies and their subsequent dissolution introduces the transition from NM in the form of an item to NM in bulk form. Large quantities of highly radioactive solutions are processed to recover U, (usually as uranyl nitrate liquors) and Pu, (first as plutonium nitrate solution and then as PuO2 powders).

In such plants, only the combination of the measurement of the U and Pu content in processed liquors performed by precise and accurate destructive analyses of samples and volume and weight determinations allows the elaboration of the NM inventory with an acceptable uncertainty. JRC’s software DAI monitors the density and volume of solutions in tanks and checks the coherency of the solution flow rates along the process. In order to do so, sensor signals are collected at high data acquisition rates. To then properly interpret these, it is necessary (i) to extract only the regions of interest and (ii) to remove the noise accompanying the information. This paper compares different filters: the centered moving average, the Savitzky-Golay filter and the centered moving median. The centered moving median is the most powerful tool for the detection of the start/end of a process step: it extracts the significant signal variation while keeping the characteristics of the signal and gives unbiased solution level (volume) results even at particular process phases such as mixing. It must be noted that this paper does not have any pretension to demonstrate by theoretical statistics means the interest of using the centered moving median in the field of process monitoring but to underline its usefulness by some practical examples.

2. JRC process monitoring software: Historian – DAI package:

Verification starts with the measurements of volume and density of solutions and the monitoring of their transfer from the accountancy tanks throughout the process, for which the JRC-Ispra DAI or Data Analysis and Interpretation software proved to be an appropriate tool [1]. Acquired volume and density relevant data are transferred from online measuring instrumentation such as pressure transducers into a so-called historian database where, on the basis of some algorithms such as the dead-band exclusion and the “swinging door” [2] data points are filtered out. For the time periods during which the signal is constant only a few points are recorded, whereas many (or all) are recorded during (fast) signal variation. All data, relevant to catch potential significant process signal changes are stored and made available for the DAI kernel.

The software is parameterized according to plant processes in order to detect different events by recognizing the sequential functional behaviors (see Fig. 1) with an accurate identification of their start and end. DAI is able to identify tank related activities such as filling, plateau, and emptying.

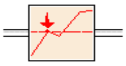
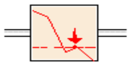
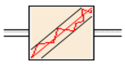
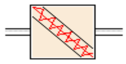
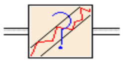
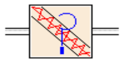
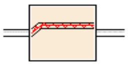
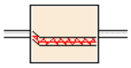
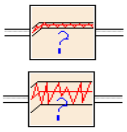
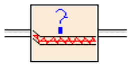
		threshold exceeded with predefined upper or lower limit
		filling/emptying with well-known flow rate (predefined mean slope)
		filling/emptying with unknown flow rate
		plateau at well-known level after filling/emptying
		plateau at unknown level after filling/emptying (with possible noisy signal during mixing)

Fig. 1: Some elementary behaviors for the recognition of process steps by DAI

The software first checks the consistency of the events with the process design by verifying its completeness and conformity with the predefined sequence of functional behaviors. Secondly, it verifies whether the exchange/transferred nuclear material is coherent by cross correlating complementary behaviors: the emptying of a tank should correspond to the filling-up of the following one in the process with a coherency check between the transferred volumes. Using the U and Pu concentrations the mass balance can be calculated in near real time.

Data interpretation must facilitate diagnostic tasks for inspectors. If an anomaly is detected, e.g. when an accountancy cycle is not coherent with the declared process, then the interpretation software must flag the event and indicate when it occurred. After which, the software should not remain in error mode but should continue analyzing the next events.

In case of a noisy signal, filtering of the regular-time-interval acquired data is necessary/preferred before they are transferred to the data historian for storage and subsequent analysis by the DAI kernel.

3. Filtering:

The purpose of filtering is to cancel out or, at least, reduce noise that may be present in a signal, consisting of a time series of data points. Filtering may also introduce unwanted effects such as a shift of the signal in time or levelling out details that are considered relevant. To avoid shifting induced by using only previous (past) data and as safeguard activities do not require any analysis at real time, we have chosen symmetric filters: the Centred Moving Average (CMA), the symmetrical Savitzki-Golay filter (SG) and the Centred Moving Median (CMQ2)[1]. The abbreviations will be followed by a number to indicate the number of points used in the filtering window. For instance, CMA_25 means that the calculated average is attributed to the 13th (central) value making use of 12 previous points and 12 subsequent ones.

These three filters were examined using the following criteria:

- Detection capability: the filtering of the signal should not impact the detection of an elementary behaviour by the Data Analysis and Interpretation software,
- Time allocation: the filtering of the signal should not influence the proper time stamping of an event[2]; in case an elementary behaviour has to be identified or repositioned manually by an inspector, the filter should not impede any manual selection of position
- Noise Reduction: the power of filtering has to be estimated by the reduction of the amplitude of the noise
- Value representativeness: the filter results should not impact the accuracy of the measured value (compared to "true" value), also during the mixing process.

[1] For the latter, to avoid any confusion between the "m" of "median" and the one of "mean", we have chosen to use the abbreviation CMQ2 as the median is the second quartile.

[2] This has as consequence the choice of an odd number of measurements in the data series, even though all filters can also be applied on even number of measurements

3.1. Centred Moving Average (CMA)

The (Centred) Moving Average filter replaces a measurement result n, part of a data series of measurement points, with the average value of the R measurement results surrounding n. With its simple principle it is definitely the most popular filter currently used to smooth time series data [3].

ℕ* being the set of all natural numbers zero excluded, the CMA performed $\forall n > (R-1)/2$ on a range of R measurements ($R \in 2\mathbb{N}^*-1$) of a data series collected at regular time intervals is represented by figure 2.

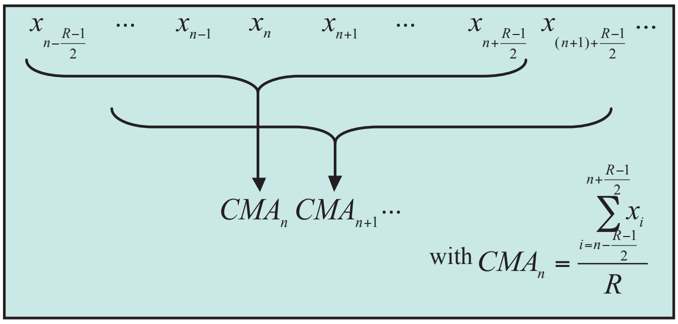


Fig. 2: principle of the Centred Moving Average

Moving average filters have two opposing properties: the wider the filtering window is, i.e. the larger the number of data points R used is, the smoother (less noisy) the signal will be, but the more the calculated values will differ from the original data. Therefore a correct balance between these two functionalities should be aimed at by selecting the appropriate filtering window.

3.2. Savitzki-Golay filter (SG):

The Savitzki-Golay filter [4] is a filter which gained popularity in the field of spectrophotometry because it allows a high degree of smoothing while preserving the patterns of the signal such as peak heights and widths.

The SG filter can be considered as a weighed moving average with weighing coefficients that can be calculated according to the order of the fitting polynomial and the number of data points framing the central one. The coefficients ($a_0 \ldots a_i$) were calculated here for a quadratic polynomial for a window of up to 25 values and are given in Annex. They apply in the following equation:

$$y_t = \frac{1}{norm}\left[a_0 x_t + \sum_{i=1}^{\frac{R-1}{2}} a_i\left(x_{t-i} + x_{t+i}\right)\right]$$

Where *R* is the window range (number of data points) and *norm* is the normalizing factor.

3.3. Centred Moving Median (CMQ2):

Even if it requires the ranking of data sets, the principle of the CMQ2 is very simple. For an odd number of measurements, as used in this study, the median is the middle measurement after arranging them from the lowest value to the highest one. While the median filter has been widely applied in image noise reduction [5, 6, 7], it is uncertain why this method has not been accepted/used, at least up to now, in the field of solution and process monitoring.

ℕ* being the set of all natural numbers zero excluded, the CMQ2 performed $\forall n > (R-1)/2$ on a range of R measurements ($R \in 2\mathbb{N}-1$) of a data series collected at regular time intervals is represented by the figure 3.

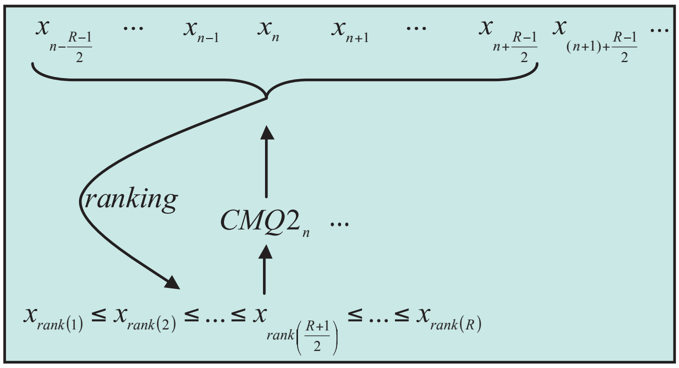


Fig. 3: principle of the Centred Moving median (CMQ2)

4. Testing:

To test the three chosen filters, we have examined the current-loop signals (mA) from pressure transducers using the dip tubes technique to determine the level and the density of a U/Pu solution in an input accountancy tank in a commercial reprocessing facility. The signal of the complete process cycle collected at regular intervals of 30 seconds is illustrated in figure 4.

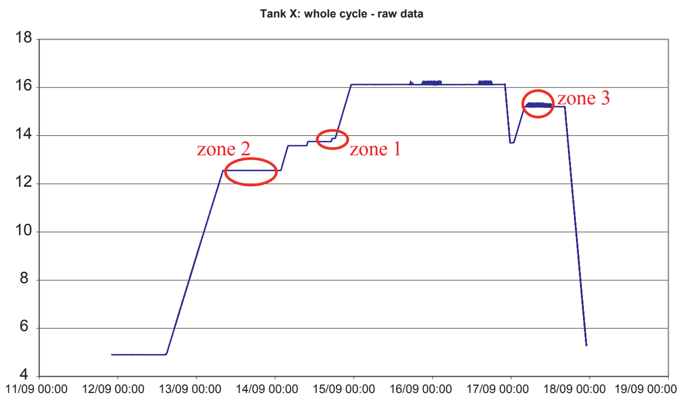


Fig. 4: level signal (mA) of a process cycle of an input accountancy tank

Three zones, identified in figure 4, were used to perform the testing. Zone 1, showing some well time-defined typical filling steps, reveals some advantages and drawbacks of the filters, zone 2, during which no modification of the solution level took place, examines the power of filtering and zone 3 verifies the filter behaviour in the particular process step of mixing.

5. Results:

5.1. Filtering of zone 1 data values: Detection Capability and Time Allocation

Figures 5a, 5b and 5c respectively show the curves obtained making use of the CMA, the SG and the CMQ2 filters. Filtering was performed on window ranges of 5, 15 and 25 values of zone 1 (see Fig. 4) and represented respectively by the yellow, green and red curves. The dark blue curve represents the raw data.

Fig. 5a clearly shows that CMA introduces time shifts (Fig. 5a, blue circles). The beginning of an event is anticipated while the end is postponed. Moreover, smoothing the signal could render correct positioning of the start/end time of a process step difficult (e.g. Fig. 5a orange circle: filling).

The SG filtering still allows positioning the filling properly. It does not introduce significant time shifts but it shows overshoots (cf. Fig. 5b, blue circles). Overshooting causes bad recognition of process steps and might trigger false alarms. As for example, the first overshoot (cf. Fig 5b – first blue circle) is interpreted by the DAI as a filling step followed by a short emptying one before reaching a plateau instead of a filling step directly followed by a plateau.

Fig. 5c shows that the CMQ2 filter does not introduce any time shift and does not cause any overshooting. All "starts and ends" of the events are respected. The start of the filling step identified by the orange circle is clearly identifiable.

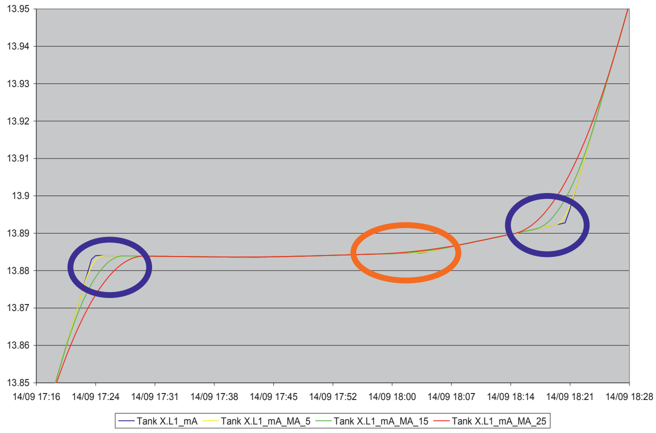


Fig. 5a: CMA on 5, 15, 25 data points of the zone 1

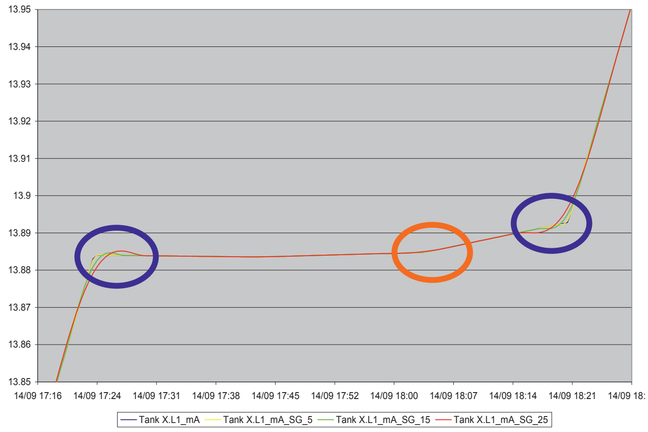


Fig. 5b: SG on 5, 15, 25 data points of the zone 1

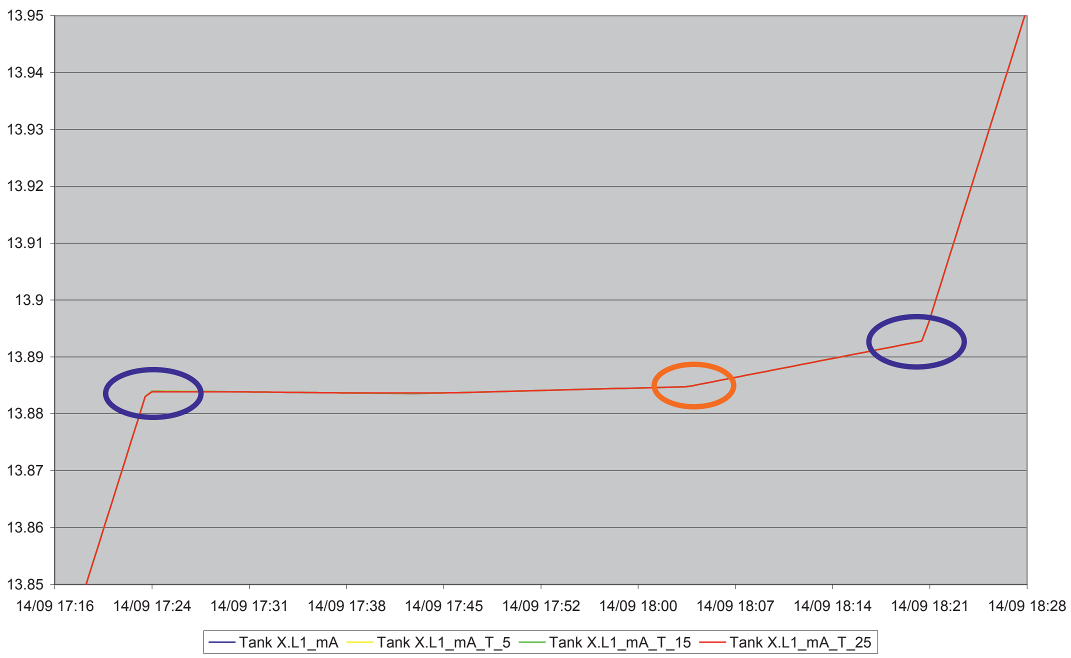


Fig. 5c: CMQ2 on 5, 15, 25 data points of the zone 1

5.2. Filtering of zone 2 data values: Noise Reduction

To compare the filtering capabilities, the CMA and CMQ2 were performed on ranges of up to 95 data points which is about the maximum window range for which CMQ2 (not CMA!) will not alter any pattern of the process cycle. This is dictated by the part of the cycle for which the inversion of the signal is the fastest. Figures 6a and 6b show that CMQ2 benefits from filtering capabilities equivalent to those of CMA while not introducing any time shift at the start/end of each process step. The red circle of Fig. 6a spots the time shifts introduced by the CMA. The SG filter was not considered in this section as its coefficients are not usually published for ranges exceeding 25 values.

5.3. Filtering of zone 3 data values: Value Representativeness

To ensure that the solution in a tank is homogenized before being transferred to the next process tank or being sampled and prior to an accurate measurement of its density, a tank cycle will always include at least one mixing step. During this process step, it is known that information concerning the level (volume) of solution and its density is biased rendering a proper control of the volume difficult. Fig. 7a and 7b show respectively the level signal filtered by CMA and SG during the mixing phase. Clearly the reported level values are higher during the mixing than before or after the homogenizing step.

Fig. 7c demonstrates the unique property of the CMQ2 to report a level value consistent with the ones preceding and following the homogenization. The signal could even be "smoother" by increasing the window of data values used to determine the median. CMQ2 allows control with continued significant values even in the case of the noisier (and more proliferation-sensitive) mixing process.

The population of the data points during the mixing was analyzed to better understand the discrepancy between the results reported by CMA and CMQ2. The results are summarized in Fig. 8. The bottom part represents the histogram with rectangle areas of equal number of data points, which is summarized in the upper part where the information on extreme values, upper and lower deciles and quartiles and the median or second quartile – red bold vertical line) and the mean value (blue bold vertical line) is depicted. The X-axis represents the current loop signal expressed in mA.)

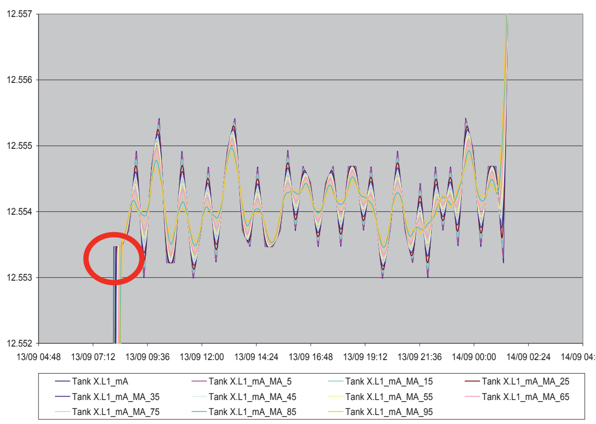


Fig. 6a: filtering of zone 2 using CMA

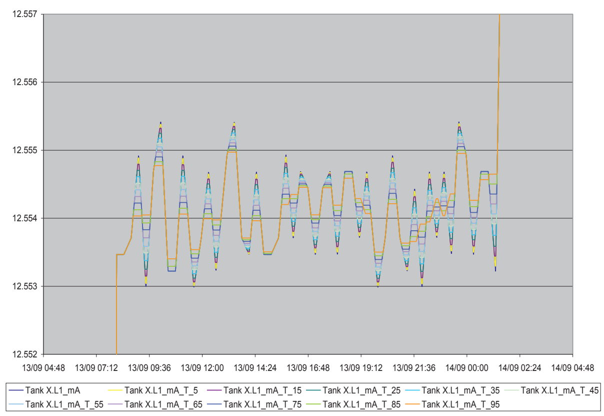


Fig. 6b: filtering of zone 2 using CMQ2

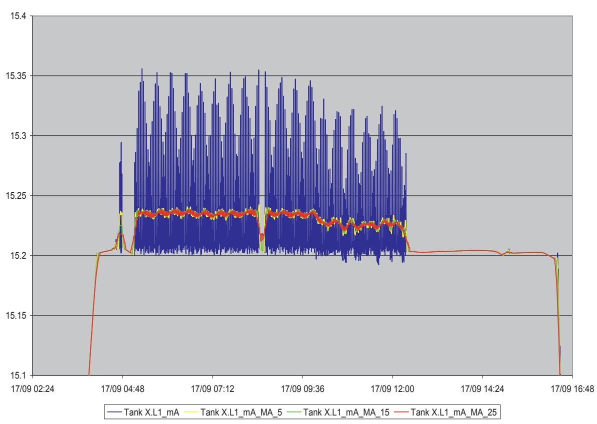


Fig. 7a: CMA of the data points of the mixing step

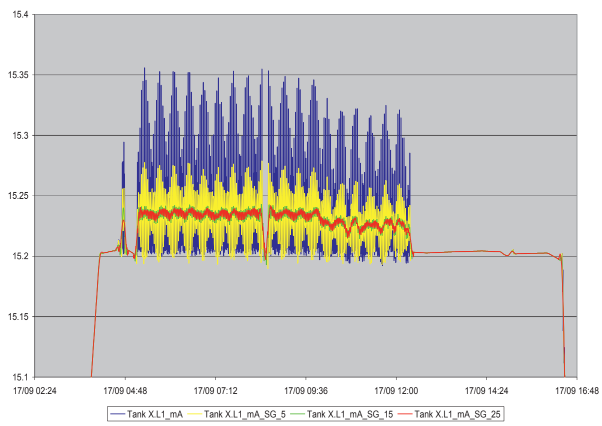


Fig. 7b: SG of the data points of the mixing step

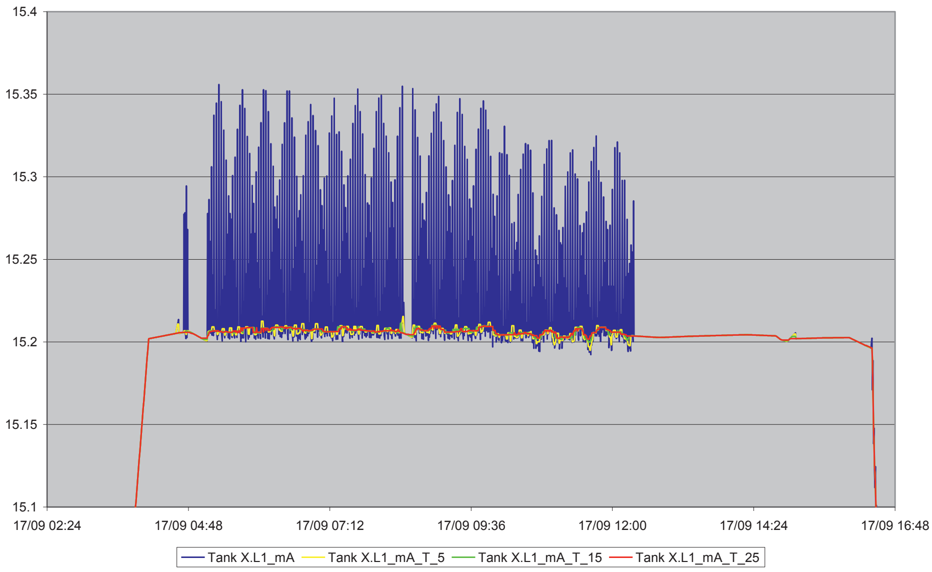


Fig. 7c: CMQ2 of the data points of the mixing step

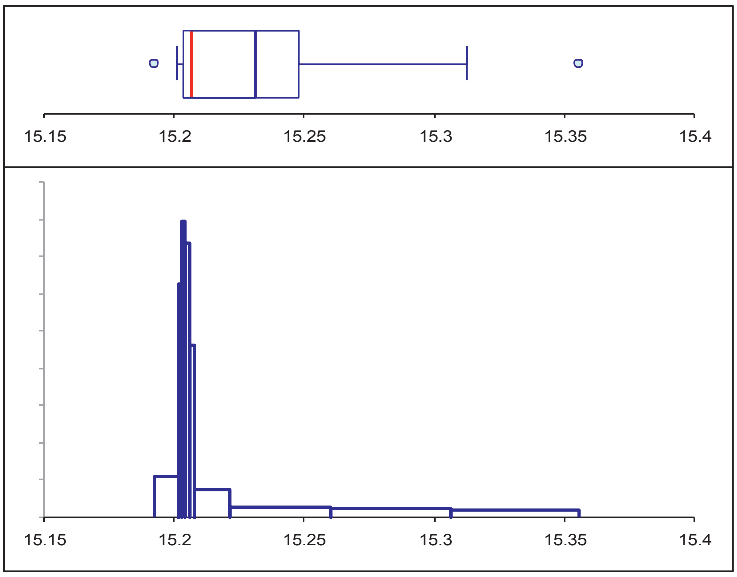


Fig. 8: box plot and histogram of the population of level data values during the mixing phase.

Fig. 8 as well as the skewness coefficient[3] of 1.4 indicates that the population of the data points during the mixing phase is not distributed normally but biased highly positively. This explains why the mean value, sensitive to extreme values, is not a good estimator of the level signal. Furthermore, the density signal for the same zone was also examined.

Figures 9a and 9b show the results obtained with CMA and CMQ2 filtering respectively.

[3] For a normally distributed population, the skewness coefficient, $\frac{n}{(n-1)(n-2)}\sum\left(\frac{x_i-\bar{x}}{s}\right)^3$, ideally equals 0. It is positive for positively biased (right tailing) population and negative for negatively biased (left tailing) population.

Fig. 9a reveals that the density signal values from CMA filtering during the mixing process are underestimated. Fig. 9b shows that density measurements can be more accurately performed by making use of the CMQ2 filter.

Here again the population distribution of the data points during the mixing phase was studied. As indicated by Fig. 10 and the skewness coefficient (-1.8), the population is not distributed normally but biased highly negatively.

Even though the positive and negative biases partially cancel out when analyzing the mass, the density and volume (via level) signals are differently influenced by ambient and operational conditions. Moreover two independently reliable signals allow a double check for safeguard purposes.

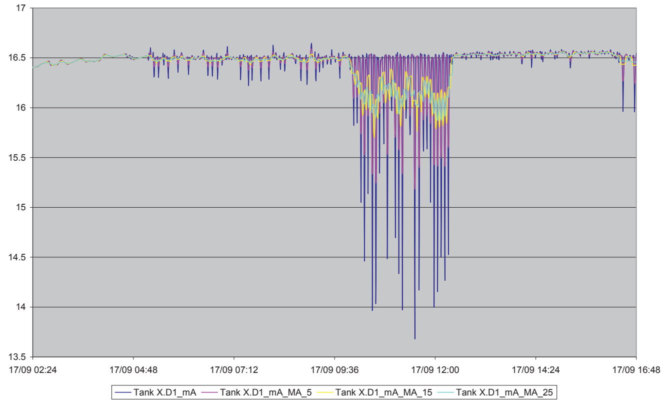


Fig. 9a: CMA filtering of density signal data points during the mixing phase

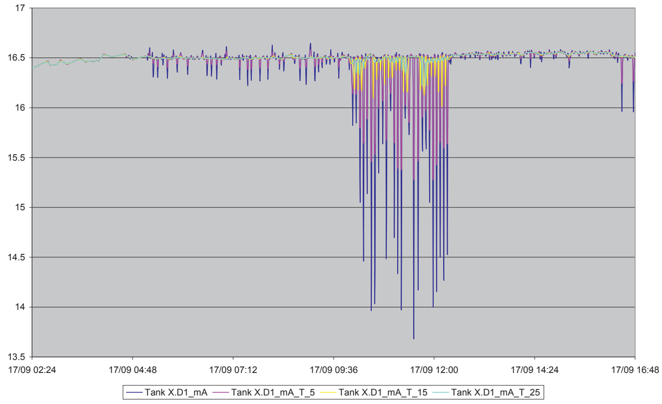


Fig. 9b: CMQ2 filtering of density signal data points during the mixing phase.

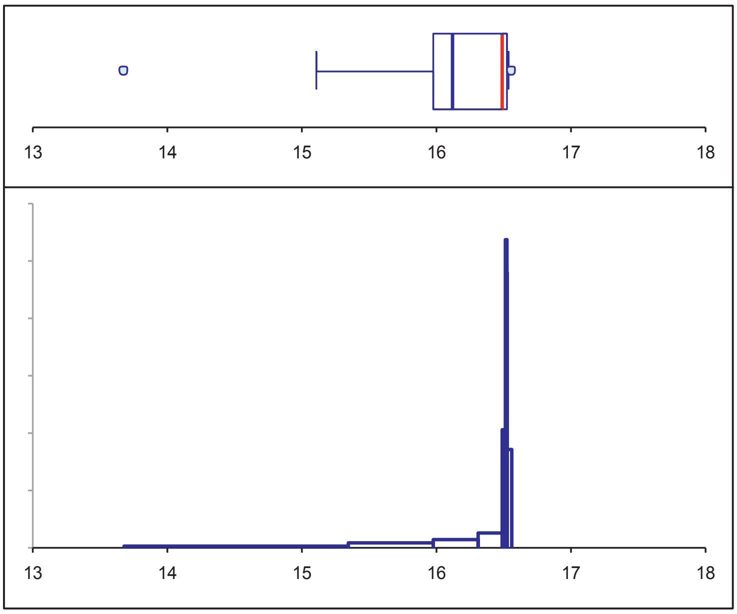


Fig. 10: box plot and histogram of the population of density data values during the mixing phase.

6. Conclusions:

This paper confronts the advantages and drawbacks of some filters for solution monitoring applications. The popular Centered Moving Average (CMA) and the Savitzky-Golay (SG) filter are not performing as well for the safeguard purpose of correctly detecting start/end of process steps as the Centered Moving Median (CMQ2). The latter also proved to be suitable for solution monitoring applications.

The CMA has the drawback of introducing non negligible time shifts. This causes starts of process steps to be anticipated and ends to be postponed introducing bias in the time stamping of the events. The SG filter suffers from overshooting which, in our special case of detection of events based on the recognition of behaviors, will lead to many false alarms of non respect of the cycle process. The CMQ2 seems to be a very interesting tool for solution monitoring, since it has same filtering capabilities as the CMA but introduces neither a time shift nor an overshoot. Moreover, during certain process steps such as the mixing phase, CMQ2 is robust as it still permits monitoring the level (volume) and density signals independently with a reasonable accuracy. Anyway, some statistics works, beyond the scope of this paper, should still be undergone even if only to determine the confidence interval to be associated with the calculated median values.

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Annex: computed Savitzki-Golay coefficients for a quadratic polynomial

R	*norm*	a0	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12
5	35	17	12	-3										
7	21	7	6	3	-2									
9	231	59	54	39	14	-21								
11	429	89	84	69	44	9	-36							
13	143	25	24	21	16	9	0	-11						
15	1105	167	162	147	122	87	42	-13	-78					
17	323	43	42	39	34	27	18	7	-6	-21				
19	2261	269	264	249	224	189	144	89	24	-51	-136			
21	3059	329	324	309	284	249	204	149	84	9	-76	-171		
23	805	79	78	75	70	63	54	43	30	15	-2	-21	-42	
25	5175	467	462	447	422	387	342	287	222	147	62	-33	-138	-253

On-Line Enrichment Monitor for UF_6 Gas Centrifuge Enrichment Plant

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Abstract:

This paper is a continuation of the Advanced Enrichment Monitoring Technology for UF_6 Gas Centrifuge Enrichment Plant (GCEP) work, presented in the 2010 IAEA Safeguards Symposium. Here we will present the system architecture for a planned side-by-side field trial test of passive (186-keV line spectroscopy and pressure-based correction for UF_6 gas density) and active (186-keV line spectroscopy and transmission measurement based correction for UF_6 gas density) enrichment monitoring systems in URENCO's enrichment plant in Capenhurst. Because the pressure and transmission measurements of UF_6 are complementary, additional information on the importance of the presence of light gases and the UF_6 gas temperature can be obtained by cross-correlation between simultaneous measurements of transmission, pressure and 186-keV intensity. We will discuss the calibration issues and performance in the context of accurate, on-line enrichment measurement. It is hoped that a simple and accurate on-line enrichment monitor can be built using the UF_6 gas pressure provided by the Operator, based on on-line mass spectrometer calibration, assuming a negligible (a small fraction of percent) contribution of wall deposits. Unaccounted-for wall deposits present at the initial calibration will lead to unwanted sensitivity to changes in theUF_6 gas pressure and thus to error in the enrichment results. Because the accumulated deposits in the cascade header pipe have been identified as an issue for Go/No Go measurements with the Cascade Header Enrichment Monitor (CHEM) and Continuous Enrichment Monitor (CEMO), it is important to explore their effect. Therefore we present the expected uncertainty on enrichment measurements obtained by propagating the errors introduced by deposits, gas density, etc. and will discuss the options for a deposit correction during initial calibration of an On-Line Enrichment Monitor (OLEM).

Keywords: UF_6, enrichment, OLEM, calibration, deposits

1. Introduction

A Continuous Enrichment Monitor (CEMO) was developed by AEA Technology, Harwell, UK in the early 1990's, with funding from the UK Safeguards Support Programme [1]. This was trialed at URENCO's gas centrifuge enrichment plants (GCEP's) at Almelo and Capenhurst [2] and has been in continuous operation on many of the enrichment cascades at Capenhurst ever since. On each of these cascades, a CEMO is installed on a product pipe at the cascade outlet, before the first valve. The CEMO offers the following advantages:

- Rapid detection of Highly Enriched Uranium (HEU).
- Automated daily reporting of state-of-health to Euratom and IAEA HQ's.
- No possibility of removal of HEU before the instrument.
- Lightweight instrument, easy to fix to a UF_6 pipe.

However, the CEMO also has the following disadvantages:

- The use of a cadmium-109 source for the transmission measurement gives rise to high maintenance costs.
- The software is now rather old and consequently the monitor is not easy to use by safeguards inspectors.
- The UF_6 gas pressure at the location where CEMO is installed is classified information and so cannot be revealed to the safeguards inspectorates.
- The UF_6 gas pressure at the location where CEMO is installed is very low and thus the resulting measurement of ^{235}U enrichment is of low accuracy (but adequate for detection of enrichment above 20% on a plant licensed to 6%).

The Advanced Enrichment Monitor (AEM) being developed by Los Alamos National Laboratory (LANL) is similar to the Harwell-designed CEMO in that it uses a sodium iodide detector to measure gamma activity from UF_6 gas in a pipe and thus will continuously measure the ^{235}U enrichment. However, the AEM is designed to be installed at a different location in a GCEP, i.e. after the pumps, which are downstream of the cascade take-off valve consoles. The AEM has the following inherent advantages over the Harwell-designed CEMO:

- The UF_6 gas pressure at the location where AEM is to be installed is much higher that at the cascade outlet, and therefore the gamma radiation from the UF_6 is much stronger.
- The UF_6 gas pressure at the location where AEM is to be installed is not classified. This means that if a plant operator were prepared to disclose the pressure measure-

ment to the safeguards inspectorates, then a cadmium-109 source would not be needed.

- On some GCEP's, the location where AEM would be installed is at a point where the take-off of several cascades has already been combined. This means with AEM, far less equipment would need to be installed in a plant than with CEMO.
- AEM should lead to a more accurate measurement of ^{235}U, at lower cost. This might even allow monitoring of tails flow, and not just product flow.

However, AEM does have the inherent disadvantage over CEMO in that it is designed to be installed downstream of the cascade take-off consoles, and so there would be opportunity to remove UF_6 before it reaches the instrument. The possibilities for an operator to defeat the instrument are thus higher than with CEMO. We must also recognise that CEMO is a proven instrument, with well over 15 years of routine use by Euratom and IAEA for safeguards verification. On the other hand, with the AEM, there is still much work to be done in testing the equipment in the field.

2. Basis of collaboration between LANL and URENCO

In May 2008, a meeting took place at URENCO's site at Capenhurst, UK, at which representatives of NNSA, LANL and ORNL proposed a trial at the URENCO enrichment plant of a Flow and Enrichment Monitor (FEMO), which was to be a combination of a ORNL-designed flow meter and a LANL-designed enrichment monitor. Over the ensuing period, it was decided to pursue testing of the LANL-designed enrichment monitor, which LANL named the Advanced Enrichment Monitor (AEM). This is being carried out within the umbrella framework of a 2001 agreement between the US and UK governments for the development and implementation of nuclear verification technologies.

In January 2011, a "project arrangement" agreement was made between the US Department of Energy's National Nuclear Security Administration (NNSA), the UK Department of Energy and Climate Change, and URENCO for a trial of the AEM in URENCO's GCEP at Capenhurst.

Also in January 2011, LANL staff visited Capenhurst, to examine the location where AEM is to be installed in the plant and to carry out some initial measurements of a prototype of the AEM, which measured the ^{235}U signal only. IAEA technical staff took part as observers during this visit. The results obtained have not yet been analysed fully and are thus not given in this paper.

It is expected that the trial at Capenhurst will continue over the next one to two years, and that a summary of the results will be published to the wider safeguards community at appropriate international conference and workshops.

3. Potential uses of AEM

There are three **potential** uses by international safeguards inspectorates of an AEM in a GCEP:

- It could be used to rapidly detect the production of HEU. Compared with the current CEMO, it offers the potential advantages of reduced cost (both of initial investment and subsequent maintenance) and improved reliability.
- It might prove to be useful for verifying the ^{235}U enrichment of filled cylinders of enriched and depleted UF_6 produced by a GCEP. This capability might replace the current methods used by safeguards inspectors to verify enrichment of UF_6 in cylinders (viz. by portable gamma-spectrometers and by mass-spectrometry of samples of UF_6).
- There is the potential for installing a complete system on AEM's on all of the feed and take-off pipes in an enrichment plant and – when combined with load cell data on cylinder weighings – to calculate the mass balance continuously. However, the system required for this would be complex and might potentially reveal sensitive information on centrifuge cascade performance.

Note that URENCO has agreed only to the carrying out of a trial of the AEM, and in so doing has not committed to implementation of the AEM as a safeguards technique in any of its GCEP's.

There are two **potential** uses of an AEM by a GCEP plant operator:

- To provide a rapid warning if the enrichment of the product being made exceeds the enrichment limit for which the plant is licensed.
- To measure the enrichment of the feed to a GCEP, and the enriched and depleted material produced. This procedure could avoid the need for taking of samples (whether on-line or off-line) for analysis by mass-spectrometry. Use of on-line gamma-spectrometry would give a continuity of measurement not realised by mass spectrometry, but is unlikely to delivery the same standard of accuracy of measurement.

At this stage, it is far too early to say whether AEM will ever be suitable for use as a working instrument for any of the above applications. Above all, the equipment needs to be reliable, easy to install and operate and cost-effective. If these requirements can be met, then it is likely that it could, in time, become an effective means of detecting HEU production in a GCEP.

4. Measurement conditions in unit header pipe

Figure 1 shows the changes in gas pressure, 235U count rate, gas attenuation and gas temperature that are anticipated to occur at the AEM location during the normal "fill

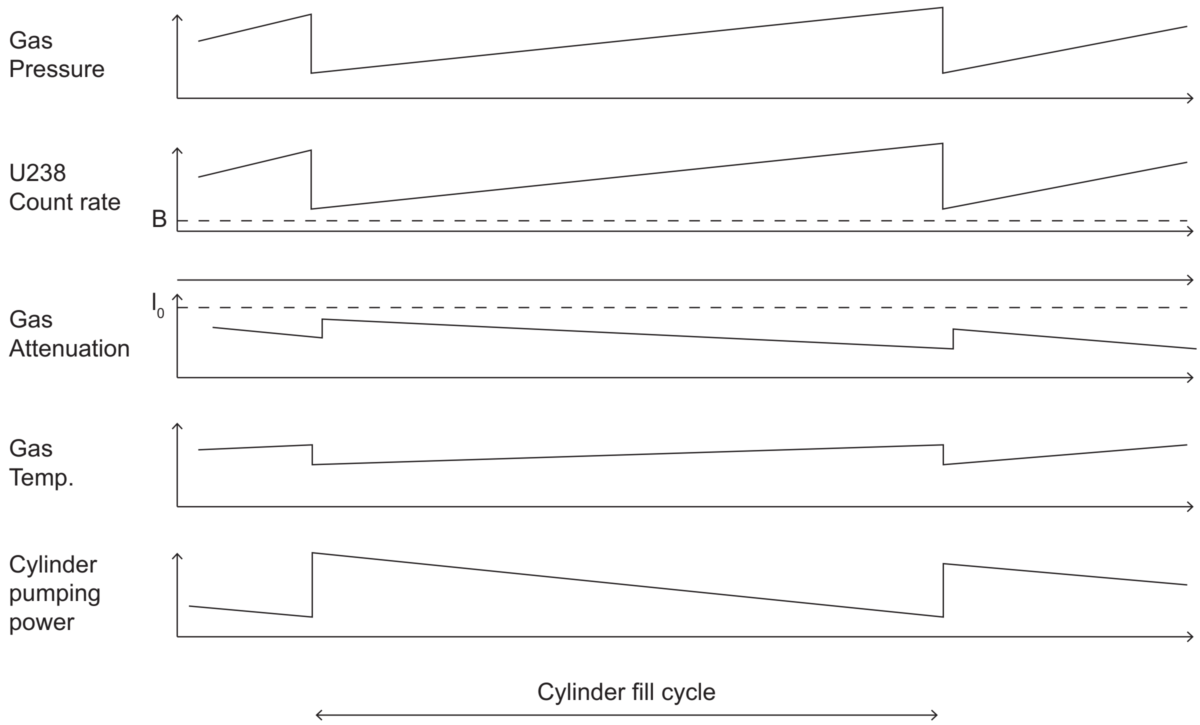

Fig. 1: Gas pressure, ^{235}U count rate, gas attenuation, and gas temperature as a function of cylinder filling.

and replace" cylinder cycle at a GCEP. These changes are used in some of the calibration options discussed below in section 5.2.

5. Active enrichment monitor (186-keV spectroscopy + transmission based correction for UF6 gas density).

Correction for UF_6 gas density in this system is based on transmission measurements similar to those implemented in CEMO and blend-down monitoring system (BDMS) predecessor technologies. Unlike CEMO and BDMS, we have replaced the use of decaying ^{109}Cd or ^{57}Co isotopic sources with an X-ray generator and "notch filter" [3]. The prototype of the system being tested in the laboratory is shown in Fig. 2. The size and weight of the existing measurement head are large and may cause installation issues. A new design with reduced size weight and stress on the pipe is shown on Fig. 3.

5.1. Measurement method

The "active" method is based on two gamma spectroscopy measurements: a) intensity of 186-keV peak of ^{235}U and b) active transmission measurement for total UF_6 gas density.

The enrichment is calculated by the formula:

$$E(t) = K_{cal}^{a} \cdot \frac{R(t) - B}{\ln \frac{I_0}{I(t)}} \qquad (1)$$

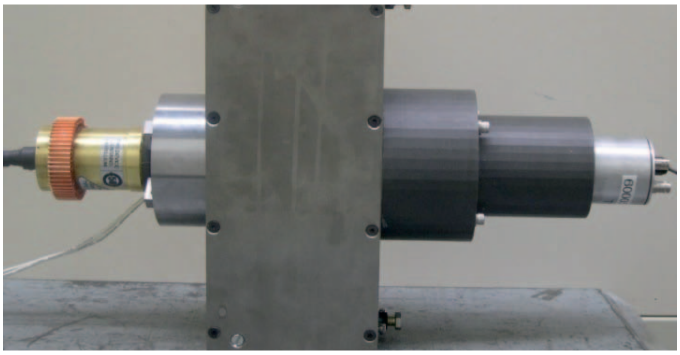

Fig.2: Existing active measurement head.

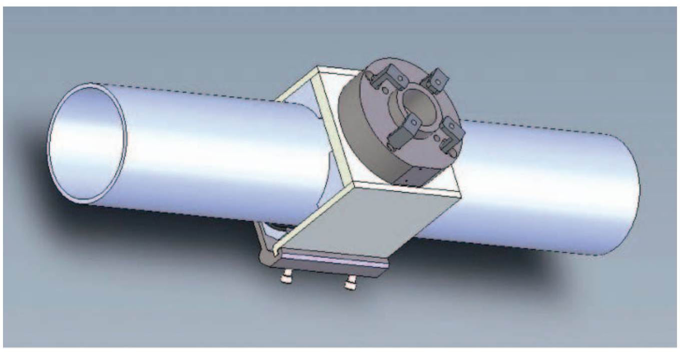

Fig. 3: Redesigned active measurement head.

where

E = enrichment (%) of ^{235}U in the UF_6 gas,

K^a_{cal} = calibration constant,

R(t) = count rate of ^{235}U, 186 keV, from UF_6 + background,

B = count rate of ^{235}U, 186 keV, from background,

I(t) = count rate of the transmission source peak **with** UF_6 gas in the pipe, and

I_0 = count rate of the transmission source peak **without** UF_6 gas in the process pipe.

5.2. Calibration options

5.2.1. Classical (empty pipe) calibration

This calibration method has been used with CEMO and BDMS systems. It relies on three measurements:

- A gas off (empty pipe) measurement to determine the intensity of 186-keV peak due to wall deposits B and transmission peak intensity without gas attenuation to determine wall deposits contribution I_0.
- Gas on (calibration) measurement to determine transmission I_{cal} and 186-keV peaks R_{cal} intensities in the moment of calibration;
- Mass spectrometry measurements to determine UF_6 gas enrichment E_{cal} at the moment of calibration.

By solving Eq.1 for the calibration constant and substituting the obtained values from above measurements we can obtain the calibration constant K_{cal} .

$$K^a_{cal} = E^a_{cal} \cdot \frac{\ln \frac{I_0}{I_{cal}}}{R_{cal} - B} \tag{2}$$

Thus, Eqn. 1 is transformed into

$$E(t) = E^a_{cal} \cdot \frac{\ln \frac{I_0}{I_{cal}}}{R_{cal} - B} \cdot \frac{R(t) - B}{\ln \frac{I_0}{I(t)}} \tag{3}$$

The classical calibration approach has proven operational history in CEMO and BDMS applications. We will use it as a reference during our field trial and testing new calibration approaches.

5.2.2. Calibration using gas pressure transients

This calibration approach is based on extrapolation of the intensities of the transmission and ^{235}U peaks at zero gas-pressure based on sets of measurements taken at different non-zero gas pressures, but with the same enrichment. This method is applicable when empty pipe measurement is not possible, or/and during the change of a UF_6 cylinder at withdraw station. We have previously experimented with this approach [9] for finding I_0 only. In this paper we describe an expanded calibration procedure for determining for both I_0 and B. Because the enrichment is the same for each pressure transient we can rewrite Eqn. 1 as follows:

$$E_1 = K^a_{cal} \cdot \frac{R_1 - B}{\ln \frac{I_0}{I_1}}; \quad E_2 = K^a_{cal} \cdot \frac{R_2 - B}{\ln \frac{I_0}{I_2}}$$

$$E_3 = K^a_{cal} \cdot \frac{R_3 - B}{\ln \frac{I_0}{I_3}}; \quad E_4 = K^a_{cal} \cdot \frac{R_4 - B}{\ln \frac{I_0}{I_4}}, \text{ etc} \tag{4}$$

Where R_1, I_1,R_2, I_2 ; R_3, I_3 R_4, I_4...etc. R_n, I_n are the transmission and ^{235}U peak intensities during transients at different gas pressures. Eqn. 4 provides us following calibration options: a) Determine I_0 and B from three sets of measurements or b) Determine I_0 and B based on fit to all available data points.

This approach could be applicable for measurement on unit header pipe where pressure transients can be used for generation of calibration data.

6. Passive enrichment monitor (186-keV spectroscopy + pressure based correction for UF6 gas density)

This system relies on pressure-based correction for UF_6 gas density, where the facility operator provides the pressure information, and therefore can use simpler hardware. The system concept and design architecture is described elsewhere [4, 5]. The installed dual-detector head is shown in Fig 4.

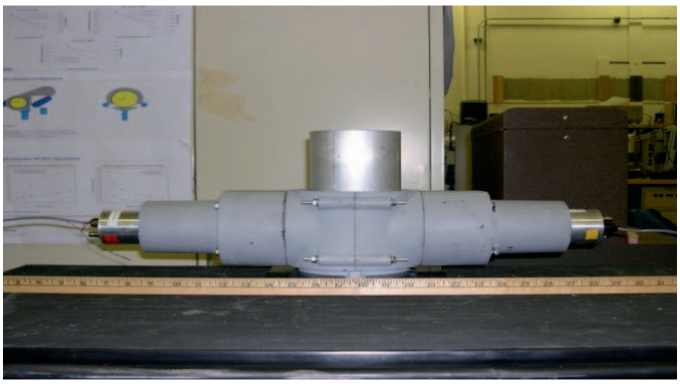

Fig. 4: Two passive detectors in the "face-to-face configuration deployed at Capenhurst.

6.1. Measurement method

For a "passive" measurement, the measurement for UF_6 gas density is provided by gas pressure and temperature according to the gas law:

$$\rho = \frac{p}{R_{UF6}T} \tag{5}$$

Where:

p is the gas pressure

ρ is the gas density

R_{UF6} is the UF_6 specific gas constant

Because the differences from the ideal gas law are small for UF_6 [6], we use an ideal gas dependency $p = \rho RT$ in our analysis and will address any nonlinearity in our calibration.

The enrichment is calculated as:

$$E(t) = K^{p}_{cal} \cdot (R(t) - B) \cdot \frac{T(t)}{p(t)} \tag{6}$$

Where:

E = enrichment (%) of ^{235}U in the UF_6 gas,

K^{p}_{cal} = calibration constant for passive measurement (that includes the universal gas constant R,

$R(t)$ = count rate of ^{235}U, 186 keV, from UF_6 + background,

B = count rate of ^{235}U, 186 keV, from background,

$p(t)$ = UF_6 gas pressure in the pipe

$T(t)$ = UF_6 gas temperature

The operator's pressure gauges provide accurate and prompt information for UF_6 gas pressure, but the gas temperature is unknown.

6.2. Dealing deal with unknown gas temperature

Because the pressure in the header pipe rises during the cylinder fill cycle, the gas temperature also will change, thus it has to be considered as an unknown variable, rather than unknown constant like I_0 and B. The correction for unknown gas temperature is the main challenge for implementation of an accurate passive enrichment monitoring system. Because the gas temperature is correlated with gas pressure, direct empty pipe or gas pressure transients calibration methods similar to an active system is not feasible for a passive system. Because both passive and active methods share the same measurement for concentration of ^{235}U, the active transmission measurement can be used to calibrate a passive, pressure-based measurement for UF_6 gas density. This would involve side-by-side measurement using both active and passive systems combined with a proven thermodynamic model of gas behaviour within the unit header pipe. Alternatively, it may be possible to determine the relationship between gas temperature and gas pressure using the passive system during a period when it is known by URENCO that the enrichment level of the UF6 is stable.

7. Conclusions

- An Advanced Enrichment Monitor is being developed by LANL and tested on a URENCO GCEP.
- The AEM has the potential to offer advantages in cost, reliability and accuracy compared with the existing CEMO.
- Both passive and active enrichment measurement methods are used in AEM development.
- Pressure transients could be used for self-calibration.
- The measurement environment at the unit product header pipe has been described.
- Unknown UF_6 gas temperature variations present a major challenge for implementation of the passive enrichment method.
- The temperature variation is related to the enrichment process, and therefore can be addressed by joint R&D efforts.

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Reference configuration for reliable and secure data acquisition and remote data transfer

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Abstract:

The Directorate for Nuclear Safeguards of the European Commission has to upgrade most of its IT infrastructure in the large bulk handling facilities of the EU in the next years. With the Data Acquisition Infrastructure Monitoring and Management System (DAIMMS) project and a reference data acquisition infrastructure based on virtual PCs on redundant servers the Directorate intends to standardise the hard- and software as much as possible to simplify the maintenance, to improve the reliability and redundancy, and to increase the security of data transfer. The early and secured separation of state of health and safeguards data will allow a separate transfer of these data and also the use of external maintenance services. The concept in detail and first field test results will be discussed.

Keywords: Data and information evaluation methodology, remote monitoring and secure data transmission

1. Introduction

In the large bulk handling facilities within the EU EURATOM Safeguards is using a lot of permanently installed safeguards equipment to follow and verify the flow of material in processing areas and the inventories of Pu (Plutonium) stores. 'Large facilities' in this context means those facilities in which Pu is handled in bulk form – for example the MOX (Mixed OXide) fuel fabrication facilities or the reprocessing plants in France and the United Kingdom. An overview of different systems, experiences and challenges is given in [1].

2. The Status of Safeguards Systems in Large Facilities Today

2.1. Installed Hardware

Today's permanently installed systems consist in general of the following hardware:

- custom made or industrial sensors such as:
  - NDA detectors together with their related electronics and high voltage (HV) supplies. (i.e. a shift registers (JSR) for neutron coincidence counting, multi channel analysers (MCA) for gamma spectroscopy, serial multichannel counters (SMC) for a simple gamma, neutron or fork detector measurements),
  - electronic seals,
  - cameras,
  - ID (identity) or bar code readers,
  - pressure gauges and level meters - outputs from other industrial sensor devices (*transducers)* (4…20 mA, voltages, switchers, etc),
- industrial PCs with interfaces such as: RS232, RS485 or CTC (Counter Timer Cards)
- network equipment such as: switches, routers, FO (Fibre Optic) converters to allow the authentic, authorised and accounted transfer of data as well as control of the sensors and PCs via VPN (Virtual Private Networks) from a central inspector office in the different installations.
- PCs or servers for data storage, review and evaluation onsite in the central inspector office.

2.2. Implemented Software

For the data acquisition and control the appropriate software routines developed under RADAR/CRISP and OPC (Object linking and embedding for Process Control) are used.

RADAR (Remote Acquisition of Data and Review) has been developed by EURATOM Safeguards over the past 13 years. It has been designed and developed in such a way that it can accommodate a standardised and fully modular software platform with RDT (Remote Data Transmission) capabilities for unattended data acquisition. Using this software package Euratom Safeguards are able to acquire data and control remotely the electronics of most of the installed safeguards devices within the bulk handling facilities. These devices include High Voltage supplies; measurement shift registers (JSR), multichannel analysers, electronic seals and cameras. There are specific DAMs (Data Acquisition Modules) that have been developed to control the range of different devices, cameras, seals, electronics, etc... In the case of a new device, such as the JSR 15, a controlling DAM needs to be developed and written. The module RADARLOG receives the data from the DAMs and creates the output as daily files for folder based storages which are being used for small and stand alone applications such as fork measurements (see Fig. 1). After an

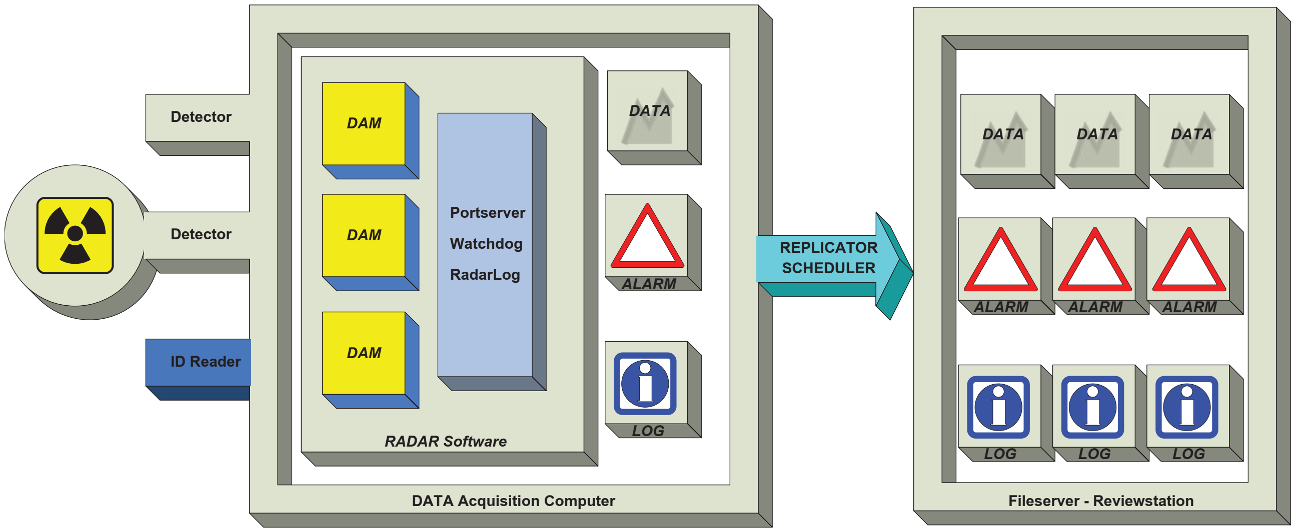

Fig 1: Unattended Data Acquisition by RADAR

upgrade in 2006 RADARLOG also is now able to fill an OPC compatible data historical database mainly used for permanently installed applications in large facilities.

CRISP (Central Radar Inspection Support Package) is a software platform to support inspectors during their review and evaluation of various sensors records. It can create events from continuously recorded RADAR files or data histories and allows a time based visualisation and correlation of different sensor events and records (see Fig 2). It is used mainly for event related measurements of itemised nuclear material i.e. the flow verification of Pu cans in reprocessing plants or pellet trays in MOX fuel fabrication plants. In cooperation with the US DOE laboratories, standard safeguards software have been modified and integrated into the CRISP package. Due to the built in features of the MGA, ORELLA and INCC software the operator declaration can be automatically compared with the value resulting from the unattended measurements.

In the last 10 years OPC has become standard software for industrial automation and is designed as a common interface for Windows based software applications and process control hardware.

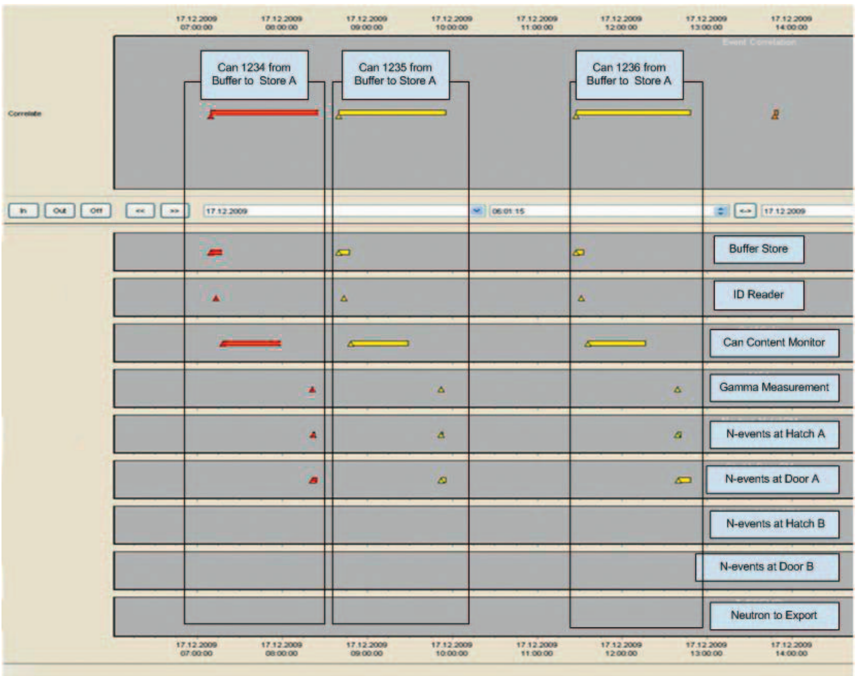

Fig. 2: Event visualisation of flow verification by CRISP – a click on the events makes the data visible

The OPC compatible PI (Plant Information) database with real-time data acquisition offers a central repository for data for a facility or across multiple locations. Information can be automatically collected from many different sources (control systems, lab equipment, calculations, manual entry, and/or custom software). Most information is gathered using one of the many PI Interfaces. Inspectors can then access this information using a common set of tools (i.e. Excel, web browsers, DAI (Data Acquisition and Interpretation)) and look for correlations, analyze trends, and compare the performance of different process areas within the plants. This software is mainly used for slowly changing values recorded by industrial sensors like pressure gauges, flow or tank level meters to allow flow verification of nuclear material in liquid forms in reprocessing plants.

The major part of data evaluation can be performed at headquarters (HQ) if the collected data are sent via RDT (Remote Data Transmission) systems as has been the case for the Sellafield site since 2007. This will increase the efficiency of inspections as inspectors will be able to concentrate on onsite verifications and resolution of open questions.

2.3. Challenges for the upgrade

The number of different hardware and software systems used for safeguards purposes has grown over the years and continues to grow. Despite the effort to standardise the sensor electronics as much as possible there are now different generations of safeguards devices and electronics, PCs, data loggers or network equipment and different software versions in the field.

The IT hardware needs to be replaced regularly. Added to this the installed instrumentation and equipment is between 5 to 10 years old. As a direct consequence of the ageing replacements and/or upgrades need to be planned.

The additional challenges associated with the replacement and upgrading include the following:

- The detector electronics, the PCs and part of the network equipment are often housed in 19” cabinets near to the detectors and are therefore located in controlled areas. This has the added complication of restricted access and maintenance work on this equipment is dictated by the internal plant procedures for working in these controlled areas.
- The increased number of permanently installed systems will necessitate more human and financial resources for installation, maintenance and upgrade, but these resources are finite and under continuous scrutiny.
- Due to changes in safety rules and the requirements of fire protection measures the status inside several cabinets are no longer the state of the art. An upgrade of these cabinets is necessary to conform to the new norms and general rules as well as ensuring future maintenance are easier.

Although the current emphasis is on improving and changing the hardware the situation with the upgrading of the software must not be overlooked. RADAR and CRISP are based on Windows XP and a migration to Win 7 (or 8) has to be investigated and planned. For more user friendliness some software parts have to be maintained or rewritten and more collected data should be evaluated automatically.

The raw data viewer ViewDAM was recently rewritten using state of the art software tools and has now been rolled out under the name VisoR (Visualisation of RADAR data).

By incorporating the existing burn-up calculation software ORELLA [5, 6] in CRISP it will soon be possible to evaluate the fork detector measurements in near real time and compare it directly onsite with the declared operator values. Further tests are ongoing to extend the software capabilities for different spent fuel geometries and different data structures of operator declarations.

3. The Reference Configuration

3.1. The Goals

In order to correctly address the hardware upgrading issues it was worthwhile to develop a concept for a Reference Configuration for Data Acquisition and Evaluation in large nuclear installations to resolve several challenges in one step. The goal of this concept was:

- to increase the dependability of the systems by built-in reliability and redundancy or diversity,
- to reduce the maintenance effort and difficulties
- to minimise the use of equipment in the controlled areas as much as possible and concentrate it in the onsite inspector offices, which are outside these controlled areas.
- to standardise the hardware and the software as much as possible in order to increase the efficiency for maintenance and repair (especially storekeeping in HQ and onsite),
- to reduce the documentation effort and the training of inspectors for the use this equipment and qualify the inspectors for help of technician in trouble shooting and equipment replacements,
- to get near real time knowledge about malfunctioning of components by remote monitoring of the status of the systems and remote data transfer to HQ (including automated evaluation of alarm and log messages) to allow quick repairs or remote maintenance
- to enable (after detailed investigation) the replacement of faulty components with the help of inspectors or local contracted maintenance personnel
- to be prepared for a remote setup, reboot and configuration of all data acquisition and evaluation systems

- to have a maintenance and replacement plan for the remaining equipment
- to perform all upgrades with reasonable costs and to have reduced maintenance costs in the future.

3.2. The Concept

The concept was to install wherever possible 2 redundant and diversified lines for data acquisition in order to minimise the risk to lose data if one component in the chain fails. All parts located in controlled areas should be simplified and have a high degree of system or component reliability. The PCs should be small, should operate without a fan and spinning components, such as hard disks, be rack mountable, and have low power consumption and redundant power supplies. Complex hardware and software which may require frequent updates, fine tuning or comprehensive maintenance should be located in the inspector office for ease of access.

Redundancy of sensors

For a variety of reasons it is often not possible to double all NDA detectors completely (costs, space, etc…) but based on our long standing intention to increase the reliability a large number of installed detectors are already equipped with a redundant output (i.e. HPGe detector preamplifiers). Most of the neutron detectors are further redundant because in each of them the HV and power input, as well as the preamplifiers, are doubled and one half of the He tubes are connected to one group, the others to a second group. The pulses of each group are added and delivered to 2 outputs. If one of the detector components breaks the counting efficiency will be reduced, but in general the detector will remain operational.

In cases were other sensors are important for drawing safeguard conclusions (i.e. ID readers, seals, cameras or process sensors) a decision has to be made whether it is possible to duplicate the hardware or if a branch of operator signals is sufficient.

Redundancy and diversity of data acquisition and storage

The sensors are the starting point for the 2 redundant data acquisition chains (example see Fig. 3).

The primary chain or system will include the dedicated sensor electronics of a JSR, MCA, SMC or PC if pulses or operator signals have to be logged. To reduce the number of PCs for data recording and controlling of sensor electronics in the cupboards in the controlled area, it was decided to replace all redundant PCs with RADAR-DAMs by a small and reliable serial server and control this serial server over a network from the inspector office, where a “hot” redundant Central Server with a NAS (Network Attached Storage) is located. On this Central Server several virtual PCs are running. Each of them control and record the data of one sensor electronics by using the appropriate RADAR-DAM. On the same server CRISP is also installed for onsite data review and evaluation. If one of the

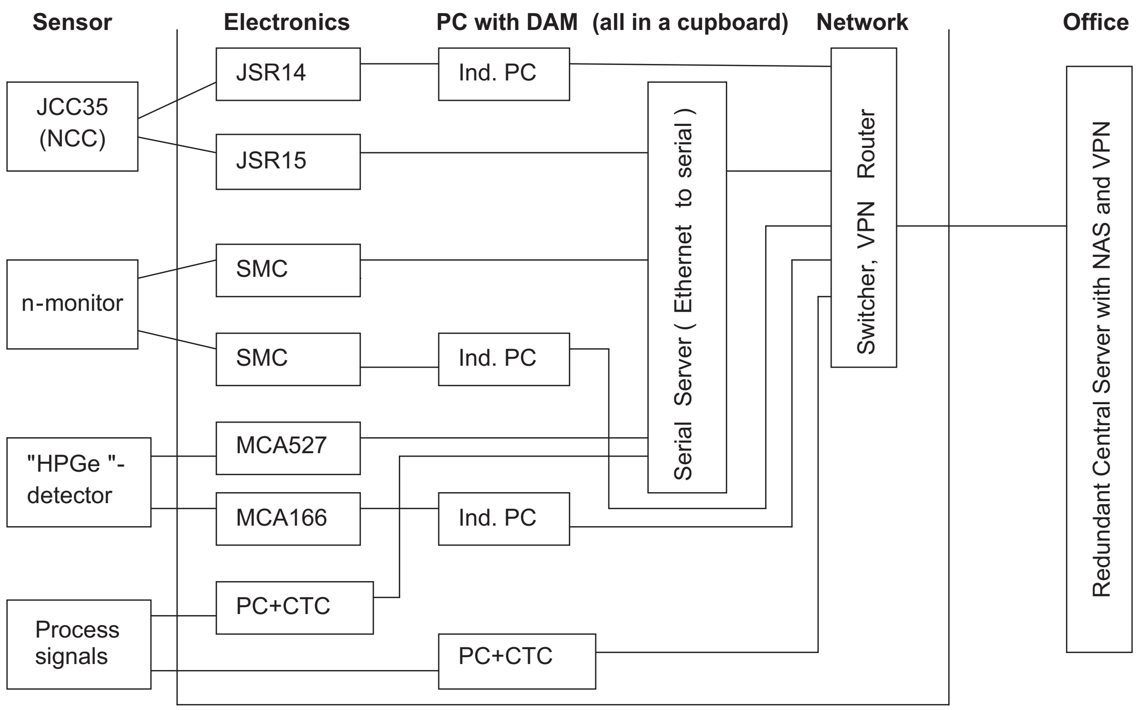

Fig 3: Example for primary (from electronics directly to serial server) and secondary data acquisition chain (via PC with DAM)

server breaks down the other will be automatically continue the job. The NAS system with built-in RAID (Redundant Array of Inexpensive Discs) system ensures that both servers use the same data set.

The secondary chain is a modernisation of the existing concept. All of the back-up sensor electronics is located in a cupboard and connected to a small, redundant powered and fan-less industrial PC. RADAR, with several appropriate DAMs, is running on this PC to guarantee an autonomous data recording and independent storage on a SSD (Solid State Disc) for several months to cover the case of failures in the primary electronic or in the network and the redundant servers. In the case that only the primary electronics or the serial server is out of order but the network and the Central Server continue to work the software could be remotely configured to use the stored data of the back-up system as an input for the CRISP algorithm. This means that a repair (or response) time of several days or weeks can be covered without a subsequent loss of data and/or performance.

The critical path in this primary system is the network, because if the out of order time is longer than the storage capacity of the sensor electronic buffer it will result in a data loss. Therefore the network should be very reliable and also redundant. However, the existing network cables cannot be doubled without incurring prohibitively costly installation and intervention so, redundancy will be achieved by intelligent switchers which are connected to each other by a ring of network cable. If a breakdown occurs on one side in the ring the switcher will automatically route the signals via the other side. This kind of network ring will be installed in MELOX (MOX fuel fabrication plant) shortly by adding cables between 3 rooms (see Fig. 4).

Important for a quick response time is the near real time monitoring of the hardware in the system. The time for discovery of an issue should be much shorter than the time after that a loss of data will occur. This time depends mainly on the power and data buffer capacity of the different hardware. For a data recording the buffer time can be easily extended to several months by having sufficient buffer storage but for power failures the response time is often less than 1 week. Therefore the power supplies of the 2 measurement chains should be separated wherever possible, but never connected to the same UPS (Uninterruptable Power Supply) to avoid common failure modes.

The DAIMMS project

In order to detect failures in near real time the DAIMMS (Data Acquisition Infrastructure Monitoring and Management System) project was launched about 2 years ago. The aim was to develop a RDT monitoring system which was capable of detecting the status of data acquisition and components status by near real time evaluation of alarm messages and routine scans of the network. The system is configured to ensure the greatest possible degree of availability and using the intelligent features embedded into the software capable of performing a continuous control. This configuration control will allow easy

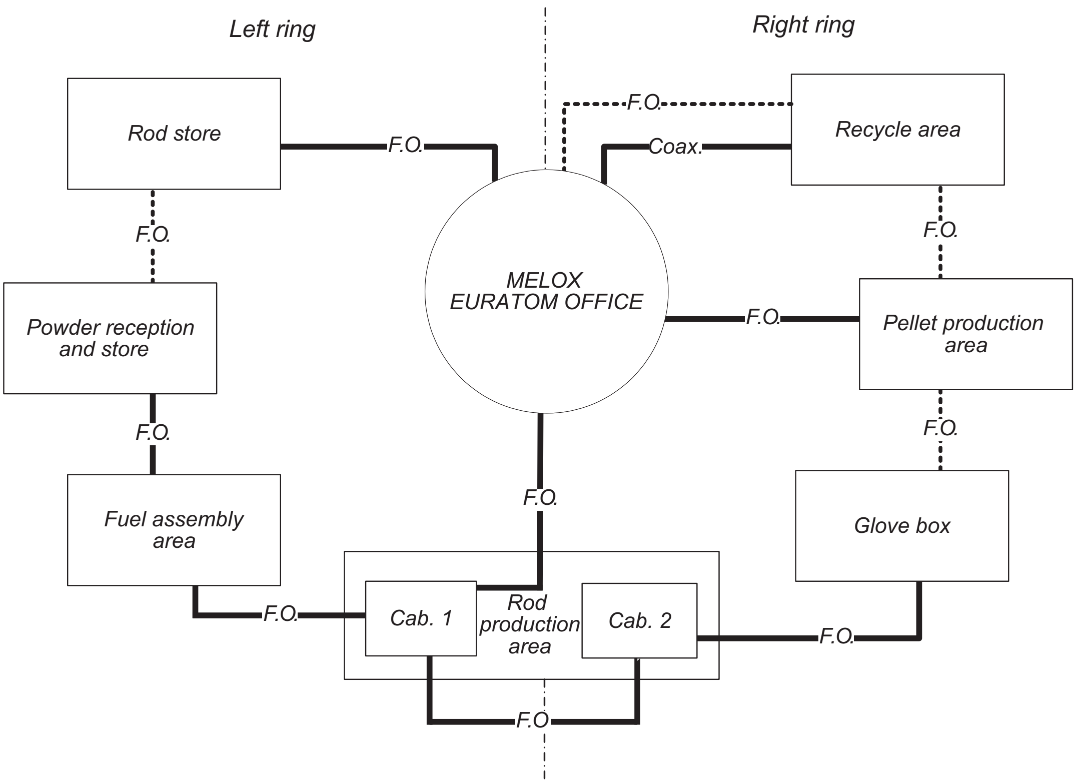

Fig 4: The future network in MELOX (full lines: existing cables, dashed lines: to be installed)

regulation of components and provide an overview of the complex system architectures, including the detection, localisation and documentation of the components of the whole data acquisition infrastructure. The visualization of the status of the different components and of their main configuration parameters completes the configuration control interface. The repeated checks of configuration, together with unattended evaluation of the SNMP (Simple Network Management Protocol) messages, identify the status of the remote devices. This management protocol enables automated parameter changes, if necessary, and the remote localisation of problems related to the devices and safeguards data. For the visualisation of the results dedicated software like “Castelrock” or “NAGIOS” can be used. It will be possible to see from HQ how the DAMs and the network (i.e. in Sellafield) are configured. It will also be possible to see if the UPS batteries are in good conditions and the stability of the installed systems.

Advanced implementation of RDT will not only allow for more efficient inspections but also will give the possibility of remote maintenance including diagnostics, preventive maintenance and bug fixing [5]. The DAIMMS also supports an early and safe separation of monitoring and safeguards data. Groups of users which have only access to the monitoring data cannot access the safeguards data and vice versa. For the large facilities this will allow the possibility to route the monitoring data to an site maintenance group, who would be able to detect and fix certain issues without the inspector presence. This idea has to be further explored and examined prior to implementation.

3.3. The Implementation

The implementation depends on the urgency of replacement needs, the progress of the different tests and the activities in the installations concerned. The implementation can be separated into 4 distinct steps:

- the tests of the virtualisation of the DAMs on Central Server
- the test of the DAIMMS project including visualisation of monitoring data
- the selection and purchase of hardware (serial server, DC power supplies, UPS and PCs) and
- the detailed plan for each project including network infrastructure improvements.

The test of the Central Server is ongoing on a mock-up in HQ. Two redundant servers and a NAS (Network Attached Storage) were installed, virtual PCs have been created and different safeguard sensors and their electronics have been connected via a serial server. The electronics are controlled by the appropriate DAMs and the whole system currently being tested. The preliminary in-house test results of the primary chain are very promising. By centralising the computer power on two servers in the inspector offices it is expected that the access for maintenance and upgrade will be easier and less time consuming, and the hardware costs will be lower, as in cases where all PCs are doubled in the controlled area.

For the implementation of DAIMMS a generic prototype has been developed and a Proof of Concept of a very sophisticated architecture was performed last year. The next steps will be the start of operation of the Network Operating Control centre for the main components installed in the remote Sellafield site as well as in the HQ machine and review rooms. It is expected to get practical experiences in the following areas:

- configuration of the SNMP (Simple Network Monitoring Protocol) suites for all sensors and electronics already offering these features,
- collecting SNMP information from RADAR functions and from the SoH (State of Health) logging files generated by UPS or other safeguards systems, such as “SDIS” and “FAST” surveillance systems to complete the coverage of monitoring by controlling all devices and functions running at the data acquisition chain,
- evaluation, visualisation and presentation of the SoH monitoring results,
- configuration of network systems to ensure high availability, confidentiality, integrity and security of data,
- ensuring strict and “impenetrable” separation between the flow of safeguards data and the flow of SoH monitoring information from remote devices
- collecting exception reports and consequent accounting of information for further analysis about the access to devices and safeguards data as a consequence of:
  - physical modifications of the infrastructure or
  - the attempt to violate secure transmission channels or
  - attacks against the authentication – authorisation mechanisms

In parallel to the tests with remote sites like in Sellafield, it is planned to implement the above mentioned features also in MELOX as a “local” configuration. This system will support the local activities endorsed by Euratom Inspectors and will locally register events in a continuous, but (as long as RDT is not in place) not in real time manner.

The selection of the important hardware components has almost been completed. The PC will be a small, fan-less, low power, version with an external 12V power supply having sufficient interfaces and plug-in extensions. The missing fan is reducing the contamination risk extremely and the external power supply allows us to implement a redundant 12 VDC power supply per cupboard with one input from operator mains and one from internal UPS. To avoid common failure modes the primary system must be powered from a different UPS compared to the secondary system. Concerning the redundant 12 VDC and UPS module

EURATOM Safeguards has gained considerable experience from former video systems. As a consequence this configuration will avoid a common failure mode resulting in a very high MTBF (Mean Time Between Failure).

The first detailed project plan was established for Melox. The network will be extended and upgraded as described in Fig. 4. The work might be finished by the end of the year. In the coming months all the cupboards in the different rooms will be gradually upgraded following the above described concept. The most challenging aspect will be the need to maintain the full functionality of the data recording systems during the upgrade activities as the upgrade will be made during continuous production.

A detailed project plan for a second site will be established in the near future. Depending on the experiences from the MELOX upgrade it may be possible to upgrade another MBA in one go.

4. Summary

The large number of different data acquisition systems used in the field, together with the necessary periodical upgrade of a lot of these systems made it essential to develop a concept for a reference configuration, which is state of the art from both the hardware and software point of view. This will allow for a better standardisation, earlier failure localisation and easier maintenance. It will also entail less training for use and trouble shooting. There will also be the added benefit of an overall cost reduction in the future due to the higher availability of data as well as an increasing number of systems that can be handled using the same human and available financial resources.

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Efficient use of low resolution personal radiation detectorsat borders

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Abstract:

In 2008, the Finnish government decided to give funding to a project for upgrading the radiation monitoring systems at the Finnish border stations. The project is scheduled for the years 2009-2014, and the total funding will be 10 million euros. The aim of the project is to enhance the radiation monitoring operation at the Finnish borders so that the ability to detect the import of radioactive substances and nuclear material is improved.

In 2010, one hundred personal radiation detectors (PRDs) were purchased. The device is an easy-to-use low-price gamma and neutron detector. It has low resolution (CsI detector) spectrum acquisition and identification properties and it is capable of identifying a number of radioactive isotopes that are most typically encountered. The identified nuclides are classified as NORM, medical, industrial or Special Nuclear Materials. This is very useful for the customs officers, providing first hand information on the type of the detected radioactive material.

Automatic analysis of low resolution spectra is not always reliable. Therefore for efficient use of spectral detectors it is imperative that the spectra can be delivered to the experts for a more detailed analysis. For that purpose every customs station will be equipped with a mini-PC and software for downloading the spectra from the detectors. The downloaded spectrum file is in the LML (Linssi Markup Language) format, which can be uploaded to a central database via a secure web page. An expert can review the spectrum and perform an independent analysis, and provide expert support to the customs officer in almost real time. It is envisaged that the spectrum alone provides sufficient information so that correct conclusions can be drawn quickly, and unnecessary interruptions to shipments can be avoided.

In this paper the hardware, software and concept of operations are described.

Keywords: radiation; detection; spectrum; analysis; customs

1. Introduction

In 2008, the Finnish government decided to provide funding to a project for upgrading the radiation monitoring systems at the Finnish border stations. The project is scheduled for the years 2009-2014. The project is done in cooperation with Finnish Customs and Radiation and Nuclear Safety Authority, STUK [1].

In Finland Customs is responsible of monitoring the flow of goods across the borders. This includes radioactive substances and nuclear materials. STUK is an expert body providing Finnish Customs expert support (so called Technical Reachback[1]).

In 2010 the joint project plan included equipping border monitoring stations with altogether 100 handheld PRDs (Personal Radiation Detectors). The selected model is equipped with a CsI spectrometer and a 1024 channel MCA and has nuclide identification capability. The system is also equipped with neutron measurement capability. This handheld device will be one of the key tools for the Finnish Customs for years to come. Four different usage scenarios are envisaged. 1) Secondary examination after an alarm from another detector, 2) Continuous personal radiation monitoring, 3) Spectrometer facilitating Technical Reachback and 4) Ad hoc portal monitor.

2. Secondary examination device and continuous monitoring

Typically the device is used for secondary examination as a handheld device that Customs officers can carry along at all times. This is the most traditional way to use personal radiation detectors and therefore it is not discussed here. Customs personnel have been trained for this kind of use. The sensitivity of the small size detector is not very high but is sufficient in most cases. Additional neutron detection capability is an important feature. Spectral identification capability helps in some cases and may allow Customs Officers to conclusions independently.

3. Spectrometer facilitating technical reachback

As the device provides automatic identification of radioactive nuclides based on a low resolution spectrum,

1 *Technical Reachback* is the capability to assist the adjudication of radiation alarms or the discovery of suspicious or unauthorized materials that could be used to manufacture illicit radioactive or nuclear explosive devices that cannot be resolved at the detection site. Technical Reachback relies heavily on radiation analysts and subject matter experts who can identify specific isotopes and potential threats based on data collected from the detection site, either remotely, or in person.

the analysis result is not always reliable. Also some other reasons may warrant for a more detailed examination of the measured spectrum, prompting the Customs officer to request expert support from STUK.

STUK has a 24/7 expert on duty system established for all kinds of nuclear and radiation emergencies. Through this system, Customs officers can reach STUK's experts for assistance. For those situations it is extremely useful that the Customs officer can send a spectrum to STUK for review. STUK has designed and set up a database for that purpose. The database is capable of receiving spectra measured in the field using various measurement systems, including the new PRD device.

In practice the Customs officers need to take the following steps. First, a spectrum is measured and stored in the memory of the PRD. Then it is downloaded to a PC with dedicated software. Finally, the spectrum is uploaded to the central database via a secure website.

The goal of the cooperation between Finnish Customs and STUK is to improve the Technical Reachback that STUK provides to the Customs. At the moment Customs officers receive Technical Reachback support by phone and fax. This practice has many drawbacks: The lack of detectors with spectrometric capability makes it difficult to perform identification and to assess the situation. Oral information transfer from the border to the Technical Reachback at STUK is sometimes ambiguous, lacking in accuracy and specificity. The communication may be biased by personal perceptions and is therefore not accurate or reliable. Information may also be incomplete. Thus, the final assessment of the case is often based on inaccurate or incomplete information.

Some of the deficiencies above will be addressed by the use of new PRDs and the renewed concept of operations. If a Customs officer needs support, he/she can call the expert on duty by phone. When the measurement is taken in the field, the spectral data can be stored in the database where it can be immediately reached by Technical Reachback. With modern encryption technologies this data can be made available via the Internet in a secured manner. The concept of operations is shown in figure 1.

4. Ad hoc portal monitor

If the PRDs are equipped with rechargeable batteries and a charger connected to the grid, it can operate

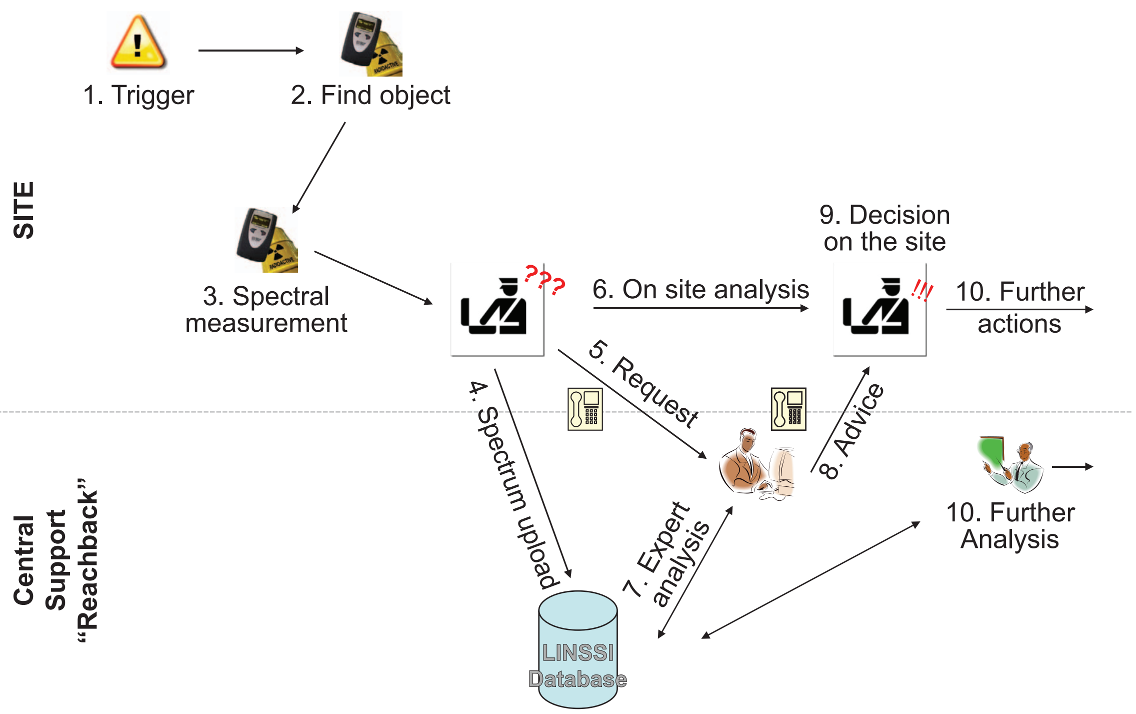

Figure 1: Concept of operations in case of PRD detection.

1. Trigger (for instance an alarm from a non-spectral portal or a continuously operated PRD).
2. The object is stopped for inspection and localized.
3. Secondary spectral measurement with PRD.
4-5. Customs officer decides to request for Technical Reachback. He/she uploads the spectrum to LINSSI database and calls to STUK's expert on duty.
6. On site analysis and assessment continues.
7. Review and analysis of the data by the expert.
8. Advice from expert to the Customs Officer in charge of decision.
9. Decision by the Customs Officer based on on-site and expert analyses.
10. Subsequent actions and analyses may follow.

continuously over long periods of time. The PRD can be connected to a small laptop or mini-PC via a USB cable; for this purpose STUK has designed a wall bracket which can hold both a PRD and a laptop. The software used to download spectra is also capable of displaying real time measuring data and announcing alarms both in numerical and graphical format. This kind of measuring system, when installed in the customs officer's booth, is able to give an alert when a source above the detection limit passes by. The detection limit depends on geometry and passing speed, but sources which elevate gamma dose rate for more than 0,2 μSv/h should be readily detected. PRDs in continuous mode will also complement traditional portal and pillar monitors, providing immediate secondary information. If alarms from both a portal monitor and a PRD go off simultaneously, one can be sure that something radioactive is approaching. The worst case scenario is that extremely highly radioactive and hazardous sources are passing the border station. In those cases sensitive portal monitors may be saturated and lower detection efficiency of PRDs is a desired feature.

5. LINSSI database functionalities

Central database needed to support the Concept of Operations presented in the previous structure exists and is in operational use. LINSSI is an SQL database for gamma-ray spectrometry [2]. It has been developed in collaboration with the Radiation Physics Group of Helsinki University of Technology, STUK, and the Radiation Protection Bureau, Health Canada. LINSSI is freely available for all registered users or for users who let the developers know that they have installed the software. Users may modify the database tables to achieve the functionality they desire.

LINSSI database was originally created to store and control successive analyses of gamma spectrometric data created by CTBT radionuclide monitoring network. LINSSI has many applications today, varying from gamma spectrometric laboratory measurement analyses to environmental monitoring performed at stationary real-time networks. Moreover, LINSSI is also in use with mobile units and in nuclear safeguards applications. LINSSI is in operational use in the external radiation monitoring network of Finland maintained by STUK.

LINSSI database is at its strongest in storing gamma spectrometric measurement data, supporting multiple analyses on the same dataset and creating multiple views to the same data. However, other types of data can also be stored. LINSSI is Linux OS based and can be installed in portable and industrial stand-alone PCs.

The user group of LINSSI has created a multitude of useful scripts and reports that can be used for border monitoring applications. Measurement data can be automatically uploaded to the database, if it is in the supported XML-type format (LML, Linssi Markup Language format). LINSSI also supports automatic gamma spectrometric analysis pipeline routines originally written for CTBT applications. These routines are successfully applied in mobile environmental measurements, which do not have specific measurement geometries. LINSSI reports are available remotely, providing analysis tools for Technical Reachback experts. In addition, successive analyses of given data can be performed online. Therefore, LINSSI can act as a seamless interface between the original data creator, automatic pipeline analysis and Technical Reachback.

6. Conclusion

STUK has procured for Finnish Customs portable Personal Radiation Detectors (PRDs). It is now the most common radiation detection tool in Finland, since all Customs offices in Finland will have it at their disposal. The device has new features like spectrometric identification capability and a continuous measurement mode, which are useful for the work of the Customs. Spectral information from the detectors will be transferred to STUKs expert, who will provide Customs officers with Technical Reachback.

7. Legal matters

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The Impact of Interdependencies on the Effectiveness and Efficiency of Safeguards

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Abstract:

The purpose of Integrated Safeguards is to evaluate a State as a whole and provide credible assurance of the absence of undeclared nuclear activities. The new system is not viewed as an addition to the traditional safeguards system but as a collection of measures to verify the correctness and completeness of the declarations.

The broadening of the scope to evaluate the State for the purpose of enhancing non-proliferation introduces uncertainties that affect the performance of the safeguards system. The processes within a State that Integrated Safeguards seeks to monitor are not clearly defined. Neither are the measurement and evaluation systems for the verification of the absence of undeclared activities. A refinement of the existing diversion process model is needed that takes into account the likelihood that a State would undertake a clandestine program.

To develop such a model this paper examines the nuclear programs of seven States that have built or attempted to build nuclear weapons and one that is being accused of having one but denies it. Analysis of the factors that are essential in the decision of a State to embark on a nuclear weapons program indicates leads to the identification of certain indicators for clandestine nuclear weapons programs. It identifies the conditions and interdependencies that most likely lead those States to undertake clandestine weapons programs and develops a set of likelihood indicators that can be used in the application of safeguards to a State as a whole. Existence of serious conflicts involving territorial disputes, transparency in the social system, militarization of the State, and democratization of the political process are the common characteristics of those States. Although these are not easily quantifiable indicators, concepts such as fuzzy logic can be used to construct likelihood estimators for the presence of absence of clandestine programs leading to a State-specific safeguards approach adapted to the conditions of each State.Thus, improving the effectiveness and efficiency requires a paradigm shift to adaptive safeguards.

Keywords: adaptive safeguards; effectiveness; interdependencies; proliferation indicators

1. Introduction

The Model Additional Protocol expands the scope of the nuclear safeguards system to cover activities and facilities that are not part of nuclear fuel cycle, but may have some relation to it. The aim of the expanded scope is to enhance nuclear non-proliferation by strengthening the effectiveness and proving the efficiency of the safeguards system. While the purpose of traditional safeguards has been to verify the accuracy of the declarations submitted by the States, the purpose of Integrated Safeguards is verification of completeness [1], [2]. Traditional safeguards consists of monitoring specific locations at specified times although inspections could take place as deemed necessary under the concept of special inspections. In other words, the domain of traditional safeguards is well defined as shown in Figure 1. Integrated Safeguards aims to apply safeguards at the state level. In doing so, the intent is to assess the proliferation potential of each State on the basis of the additional information collected by the IAEA.

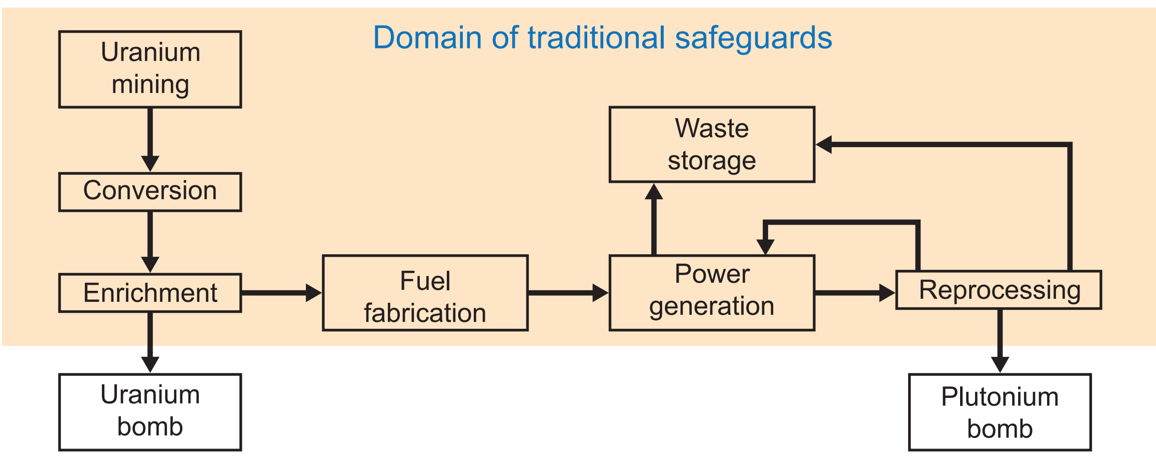

Figure 1: The domain of traditional safeguards

Looking beyond the details of the two safeguards systems, one can identify a fundamental conceptual difference between them. While the objective of traditional safeguards is clearly the detection of diversion from declared fuel cycles, the purpose of the expanded safeguards is to detect nuclear materials and activities, in other words, nuclear weapons programs in whatever form and stage of development those might be [1]. Since weapons development programs comprise a broad range of activities that can be dispersed in many locations, the quantity and types of information necessary for the application of Integrated Safeguards are much greater than those for traditional safeguards that are applied to the well defined process of the nuclear fuel cycle.

The crucial element for the good performance is the detailed definition of the observed process and the monitoring system that has been designed to observe the entire process. In contrast, under the concept of Integrated Safeguards, there is no definition of the process integrated safeguards are supposed to observe other than to verify the absence of undeclared activities anywhere in the State [3]. The absence of a model for nuclear weapons development at the state level introduces many uncertainties that affect the performance of Integrated Safeguards. As shown in Figure 2, the domain of Integrated Safeguards, in addition to the well defined nuclear fuel cycle, includes other activities such as planning, theoretical research, e. t. c., which are not as clearly defined.

An important factor that is bound to play a significant inhibiting role in arriving at credible conclusions about the absence of nuclear weapons programs is the qualitative nature of some of the information acquired under the terms of the Additional Protocol. One approach to overcome this difficulty utilizes fuzzy logic concepts [4], [5]. Another uses of probabilistic models [6], [7]. Both aim to identify critical elements in various stages of the fuel cycle that could be used as indicators of diversion. The presence of one or more such indicators would be sufficient to detect violation without the need to do a complete materials balance. These techniques are potentially useful when they are applied to well-defined processes such a reprocessing plant or similar facility. It is not clear how they would apply to a distributed nuclear weapons program at the early stages of its development where nuclear materials are not involved, but all the components of the weapon are designed, assembled and tested.

An alternative approach toward the development of procedures for implementing Integrated Safeguards is to develop a model of nuclear weapon proliferation. The existence of one or more models of probable proliferating States would aid the IAEA in optimizing the allocation of its resources effectively and efficiently. The approach presented in this paper is to develop profiles of proliferating States using empirical data.

2. The proliferation landscape-States with nuclear weapons programs

To develop an effective detection system for nuclear-weapon proliferation a fairly accurate model of the process is needed. Using as a reference point the desire to prevent "wider dissemination of nuclear weapons" as articulated in the preamble of the NPT, a profile can be constructed of the state of proliferation from the time of the signing of the NPT to the present. This time line spans more than forty years of experience, an interval sufficiently long for providing enough data to form a reasonably good snapshot of the proliferation process. A State that has undertaken development of nuclear weapons is a proliferating State regardless whether or not it has signed and ratified the NPT. Following is a brief

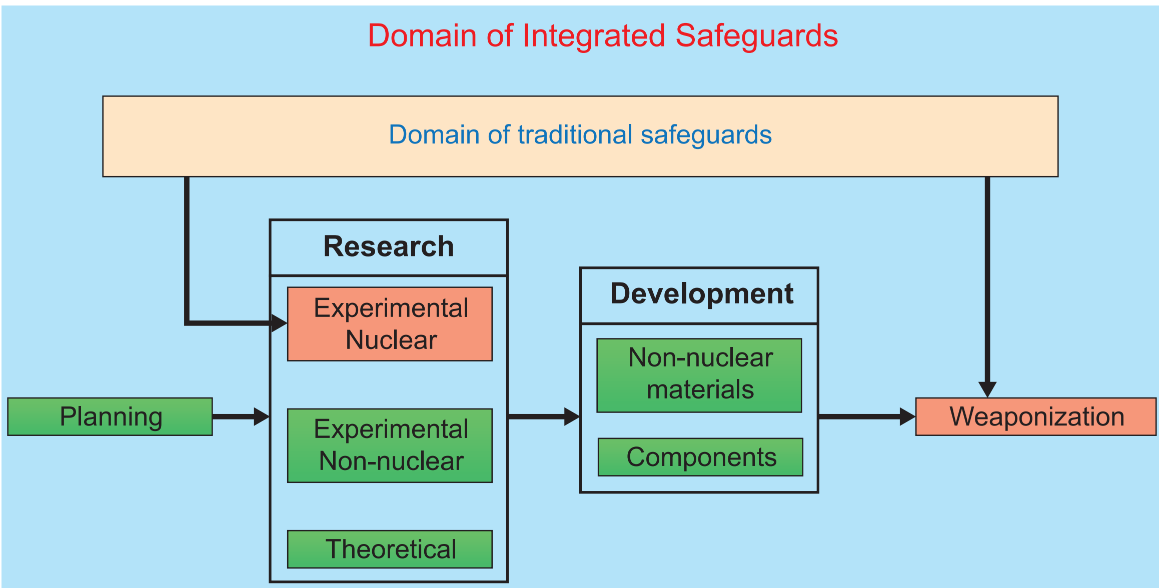

Figure 2: The domain of Integrated Safeguards includes some ill-defined elements

history of nuclear weapons programs of States, excluding the five Nuclear Weapon States, that either have acknowledged the existence of such programs, have been found to have clandestine nuclear weapons programs. It could be argued that the Nuclear Weapons States should also be included in the set of States used in the development of such a profile. For the purposes of this paper they have been excluded, because the concept of nuclear proliferation, by definition, uses these States as a reference point. It would be appropriate to include them for developing a model for nuclear weapon States in general.

2.1. The South America landscape

Argentina started a nuclear research program in 1953 [8], [9]. It is not clear whether the purpose of the program from the beginning was to develop nuclear weapons, or that the program started as a nuclear energy research program and subsequently branched into a secret weapons program. In the late 1960s Argentina had built a small scale reprocessing facility to produce plutonium and in 1978 had constructed a secret facility for the production of highly enriched uranium. The program was formally terminated in 1983 when a democratically elected government replaced the military junta that had taken control of the country since 1978. The impetus for starting such a program was provided by the concern that Brazil might be having such as program. In other words, the motivation was for Argentina to develop nuclear weapons as a deterrent against a perceived nuclear threat from Brazil. The concern was put to rest when democratically elected governments in Argentina and Brazil agreed to cooperate on peaceful uses of nuclear energy. Argentina terminated its weapons program, because the need to have such weapons vanished. Argentina became a party to the NPT in 1995, considerably later after it stopped its nuclear weapons program.

The nuclear weapons program in Brazil proceeded in parallel with that of Argentina [8]. Brazil had started conducting nuclear research as early as 1935 [10]. By 1953 its nuclear research program had both civilian and military components, with the various branches of the military developing their own secret programs. As in the case of Argentina, rivalry between the two neighbours was the primary motivation for Brazil's pursuit of nuclear weapons. As relations with Argentina improved, in 1990, Brazil renounced its interest in developing nuclear weapons and acceded to the Treaty of Tlatelolco in 1993 and to the NPT in 1998. Brazil accepted IAEA safeguards in its civilian facilities in 1997, much later than the date when it formally terminated its nuclear weapons programs.

2.2. The South Asia landscape

The beginning of India's nuclear weapons program may be traced to its beginning as an independent State after the colonial rule. In 1944, Nehru declared that "if India is threatened she will inevitably defend itself by all means in its disposal" [11]. One can surmise that India perceives the threats to emanate from China and Pakistan due to the unresolved border disputes. As early as 1958 India started to work on plutonium reprocessing and intensified its effort to develop nuclear weapons particularly after the first Chinese nuclear test in 1964 [11]. The first nuclear weapons test was done in 1974 followed by more tests in 1998. In total India has conducted six nuclear tests, but the size of its nuclear arsenal is not known.

It is easy to see the causal relationship between the nuclear weapons program of Pakistan and that of India. Like India, Pakistan has not signed the NPT. Nevertheless, after India had made substantial progress in developing nuclear-weapons capability, Pakistan embarked on a similar program in the early 70s following its defeat in the war with India in 1971. More so than India, Pakistan's nuclear program has benefited from information received from sources outside Pakistan. China has an ongoing cooperation with Pakistan in the nuclear field. Even more important is the reprocessing know-how A. Q. Khan obtained surreptitiously from URENCO and took it with him as he went to Pakistan to lead the fuel enrichment program. In 1998 shortly after the Indian nuclear tests, Pakistan also conducted its own nuclear tests. For the tests to be conducted shortly after those of India, it would be reasonable to conclude that Pakistan had already built all the components and made the final assembly in reaction to the tests by India.

2.3. The Middle East landscape

The nuclear landscape in the Middle East is directly affected by the unresolved Palestinian issue and the border dispute between Iran and Iraq. The three major actors are Israel, Iran and Iraq, although other States may have also considered the option of nuclear weapons.

Israel has not signed the NPT and has not formally acknowledged that it has nuclear weapons, although there have been indicators pointing to their existence. Nuclear research in Israel started as early as 1949 [12]. In 1986 Mordechai Vanunu, a technician at the Negev Nuclear Research Center, revealed that Israel had built and possessed nuclear weapons. There are suspicions that the flash detected by the VELA satellite over the Indian Ocean in 1979 was a nuclear test conducted by Israel, possibly with the cooperation of South Africa. The suspicion is that Israel's nuclear weapons program started a short time after it had signed the first nuclear cooperation agreement with the United States in 1958.

The discovery of a secret nuclear weapons program in Iraq provided the impetus for the re-evaluation of the original safeguards that were applied to declared facilities. The discovery was the more jolting by the fact that the clandestine program was taking place in a facility that was under IAEA safeguards precipitating a re-examination of the effectiveness of the facility-oriented approach. Iraq signed the NPT in 1968 and ratified it in 1969. The IAEA started applying safeguards in 1972. Shortly after the bombing of the Osirak research reactor by Israel in 1981, Iraq embarked on a crash research program to develop nuclear weapons capability and started a uranium enrichment program using indigenous technology [13]. In spite of the IAEA inspections the program was not detected for two main reasons. Some technology was not imported, but developed indigenously using commercially available components, while other was purchased in the black market; also, indigenous technical expertise was augmented by expertise procured in the international market. After the defeat of Iraq in the Gulf war of 1991, the IAEA found Iraq in violation of its safeguards obligations, because it had carried out research and development enrichment and reprocessing activities both at declared and undeclared facilities [14]. UNSCOM began wide-ranging inspections that discovered the extensive weapons development program. As in the case of Israel, the details of Iraq's nuclear weapons program were revealed in 1995 by an insider, a defecting official of the Iraqi government. The information provided in conjunction with the intensive inspection effort on the ground allowed the IAEA to conclude that by 1998 Iraq had no longer a nuclear weapons development program. When UNMOVIC suspended inspections in 2003 the IAEA was again able to report that there was no evidence the weapons program had been re-started [15].

Iran, at various times starting in the decade of the 1980s, has been accused that it is developing nuclear weapons in secret. In contrast to Iraq that acknowledged the existence of the secret program, albeit under unusual conditions, Iran has always asserted that its nuclear program is solely for peaceful purposes and that it is in compliance with its safeguards obligations. The nuclear program started in the 1970s under the reign of the Shah with nuclear research activities. It continued after the revolution in 1979. The seize of the US Embassy in Tehran that year precipitated a confrontation with the US that lasts to this date. The first sanctions were imposed after the seizure of the Embassy followed by another set after the bombing of the U.S. Embassy and marine barracks in Beirut in 1984 and the labeling of Iran as "sponsor of international terrorism". Additional US sanctions were imposed in 1992, 1995, 1996 and 2000 amid accusations that Iran embarked on a program of nuclear weapons development [16]. In 1980, Iraq invaded Iran starting a war that lasted until 1988 that saw the use of chemical weapons first by Iraq and eventually by Iran. Toward the end of the decade of the 1980s and the beginning of the decade of the 1990s, Iran intensified its nuclear program that included research and development activities in reprocessing and enrichment. It sought to import technology from various sources including China and Russia and Pakistan [8]. The scope of the Iranian nuclear program became multifaceted ranging from power generation to research reactors, enrichment and reprocessing. As the import of technology became problematic due to the broadening of the sanctions regime Iran has intensified its efforts to develop indigenous capabilities for all stages of the fuel cycle. The IAEA inspections of the declared facilities since the signing of the safeguards agreement have not found any evidence of non-compliance. As late as 2009, the IAEA continued to verify non-diversion of nuclear material. However, in 2002, an Iranian resistance group revealed that Iran was engaged in nuclear activities at undeclared sites (Natanz and Arak) for which subsequently Iran submitted declarations. The IAEA also raised questions about previously undeclared nuclear material and asked Iran to suspend enrichment as a confidence-building measure. Iran did so and signed but has not yet ratified the Additional Protocol. In 2006 the UNSC passed a resolution demanding that Iran suspend its enrichment activities. Following Iran's refusal to abide, the UNSC imposed a series of sanctions that are in effect to this date [16]. In the meantime, the US has woven a web of sanctions that cover, in addition to nuclear-fuel cycle technologies, potential dual-use technologies and, practically, all transactions involving Iranian financial institutions. Following the imposition of these additional sanctions, Iran resumed and expanded the enrichment activities at Natanz. In a further escalation of the pressure on Iran there have been multiple calls in the US and Israel to bomb the Iranian nuclear facilities.

2.4. The East Asia landscape

The Korean War ended with an armistice in 1953 that divided the Korean peninsula into a north and a south part, the Democratic People's Republic of Korea (DPRK) and the Republic of Korea (South Korea); the state of war persists to this day. Since 1953 the United States has a Mutual Defense treaty with South Korea that allows, *inter alia*, the stationing of US forces in the territory of South Korea. A similar treaty was signed with Japan in 1954. The DPRK ratified the NPT in 1985 and signed a safeguards agreement with the IAEA in 1992. Initial inspections by the IAEA of the research facilities at the Yongbyong complex revealed inconsistencies with the data provided by the DPRK. As a result, the IAEA, in 1993, requested a special inspection to resolve the inconsistencies. The DPRK refused the special inspection and announced its withdrawal from the NPT. The IAEA considered the withdrawal illegal and found the DPRK in non-compliance with its safeguards agreement. It founded it again in non-compliance in 1994, after it began removing fuel from the reactor without the presence of IAEA inspectors. In response, the DPRK withdrew from the IAEA. These events led to the start of negotiations between DPRK and the United States that led to an agreement that provided for the DPRK to freeze the activities that had raised proliferation concerns and accept IAEA safeguards, in exchange for being provided with light water reactors and other energy supplies by the Korean Peninsula Development Corporation (KEDO) [17]. The agreement also provided for measures to be taken to reduce tensions in the

Korean peninsula. A significant factor contributing to the high level of tensions is the heavy military presence across both sides of the demilitarized zone. In 2004 the President of the United States declared that the DPRK was a member of the "axis of evil". DPRK responded by revealing the existence of a program to enrich uranium for nuclear weapons, KEDO suspended the supply of heavy oil and DPRK expelled the IAEA inspectors. In 2003 it withdrew from the NPT and in 2006 it announced that it would conduct a nuclear test and did so [8].

2.5. The Africa landscape

South Africa had a nuclear research program long before it joined the NPT in 1991 and accepted IAEA safeguards. It had, however, been a member of the IAEA since 1957. With an extensive mining industry South Africa explored the feasibility and produced a plan for developing nuclear devices for peaceful uses [18]. In 1974, in the context of the Cold Ward and the upheavals in central Africa, the government of South Africa embarked on a secret program to develop nuclear weapons. Indications of the existence of the program were first given by the Soviet Union in 1977 when it detected preparations for underground testing through satellite surveillance. In 1979 the United States also confirmed the existence of a nuclear weapons program. Although sanctions had been imposed since 1979 they did not stop the program. South Africa abandoned nuclear weapons in 1989 as the Soviet Union collapsed and the political landscape on South Africa's north was changing. At the same time the minority apartheid regime realized that its rule would eventually be coming to an end. In 1993 the South African government announced that it had destroyed six nuclear weapons that it had built in the past. A democratic government replaced the apartheid regime in 1994.

Libya revealed almost explicitly in 1996 its efforts to acquire nuclear weapons when it cited the need for the development of nuclear weapons by the Arab States as a deterrent to a nuclear-armed Israel. While South Africa made nuclear weapons relying primarily on indigenous capabilities and resources, Libya, at the other end of Africa, attempted first to buy the weapons and failing that to import the technological capacity and manufacture the weapons domestically. The illicit nuclear supply network organized by A. Q. Khan played a major role by providing Libya with an enrichment plant on a turn-key basis [14]. Nevertheless, Libya was nowhere close to building a bomb after two decades of effort. Since 1992 Libya had been under UN as well as other unilateral sanctions for the downing of Flight PANAM 103 over Lockerbie, Scotland. In 2003, Libya began a series of negotiations with the United States and the United Kingdom seeking to end its international isolation. In the process, it revealed the existence of its nuclear weapons program and agreed to end it. Although Libya had ratified the NPT in 1975 and accepted IAEA safeguards in 1980, it was found in violation of its safeguards obligation in 2004 after it had revealed the existence of its secret program [14].

3. Characteristics of proliferating States

A close examination of the States that have been identified, or for which strong suspicions have been voiced, as having nuclear weapons programs reveals that they share some common characteristics.

Nuclear weapons have proliferated in regions where there have been festering and unresolved conflicts over long periods. There is a direct connection between most of these conflicts and colonialism. Although the unresolved conflict in the Korean peninsula does not have a direct connection with colonialism, it has its origins in the division of Europe and Asia into two political and military camps following the end of the Second World War.

In all cases the proliferating States felt threatened by one or more neighboring State. India first built nuclear weapons on the basis of the same rationale as that of the United States and the Soviet Union, namely, deterrence against its nuclear-armed adversary, China. This, however, caused a reaction, not so much by China, but by Pakistan that has been in conflict with India since its creation as an independent State. The fact that Pakistan conducted nuclear tests within a relatively short time following the nuclear tests by India leads to the conclusion that Pakistan had linked its nuclear weapons program to that of India.

Another example that nuclear proliferation is linked to the existence of a conflict is the Middle East. The all but acknowledged possession of nuclear weapons by Israel is its policy of maintaining military superiority in the region. Israel has sought to achieve and maintain overwhelming military superiority in the Middle East since its creation. It was not very difficult for Iraq to conclude that after the attack against the Osirak nuclear research reactor, the only way to achieve parity would be to build nuclear weapons. While Iraq was cognizant of its military inferiority vis-à-vis Israel, it must have calculated that it had military superiority vis-à-vis Iran that would allow it to achieve its objectives. When Iran wasn't as easy a target as Iraq had calculated, it used chemical weapons contrary to its obligations not to do so under the Geneva Convention to which it was a signatory.

The third link in the proliferation landscape of the Middle East is Iran. It is being accused of having a clandestine nuclear weapons program, but it insists that its extensive nuclear program is for peaceful uses. It is subject to unilateral and multilateral sanctions and it is being threatened by military attacks. It is an open question whether or not Iran has a clandestine nuclear weapons program. If it does, the reasons for doing so would be very obvious; it would view nuclear weapons as a deterrent as the other States that have developed them have done.

The existence of conflict also forms the background for the development of nuclear weapons by the DPRK. However, unlike the other States that undertook weapons development programs in secret, the DPRK made little effort to conceal its program. No special skills were needed to detect the existence of the program when the DPRK withdrew from the NPT after the IAEA sought to clarify discrepancies in the original declaration. One can conclude that the DPRK has embarked on the nuclear weapons program as a deterrent to the overwhelming superiority of the South Korea-US alliance.

That conflict is an important predictor of proliferation is also shown by the cases of termination of nuclear weapons programs when tensions subsided. South Africa acknowledged that it had built nuclear weapons in reaction to the perceived influence of the Soviet Union in the region. With the collapse of the Soviet Union, the threat disappeared along with the need to have a deterrent based on nuclear weapons. In addition, concerns were raised within the South African government about the security of the nuclear weapons given the uncertainties associated the collapse of the apartheid regime. These two factors the government of South Africa to terminate the program and destroy the existing stockpile.

End of a different form of conflict is also associated with the termination of Libya's nuclear weapons program. Termination was the outcome of a cost-benefit analysis done by the government of Libya. After years of being subject to international sanctions and in political isolation following the downing of the airliner over Lockerbie, the quid pro quo for Libya to be re-integrated into the rest of the world was the termination of the programs for developing weapons of mass destruction. It should be pointed out, however, that Libya, unlike all the other States with on-going weapons programs, was not in conflict with its immediate neighbors. Thus, there was no evident need for nuclear deterrence which made the cost-benefit calculation easier.

Closely linked to the existence of conflicts is the form of government the proliferating States have. They all exhibit some degree of militarism. Although there are no clear-cut divisions, the majority are authoritarian in nature with the exception of India that has had a functioning democracy since independence while maintaining a strong military establishment. Israel and South Africa are special cases that share similar characteristics. In South Africa under apartheid, there was a functioning democracy within a subset of the population that was keeping the majority under control by force. Similarly, Israel is a functioning democracy for the Jewish subset of the population, while it uses force to control the Palestinians. Of the other States, Iraq under Saddam Hussein was a dictatorship as the DPRK continues to be. To a lesser degree Pakistan is also a militarist State, because the military has overthrown elected governments a number of times and still yields substantial influence over the affairs of State.

The development of nuclear weapons programs has also been influenced by the industrial profile of the proliferating States. Libya, with a rudimentary industrial and technological base tried the obvious way of attempting to purchase nuclear weapons. When that failed, it attempted to develop indigenous capability through a combination of domestic effort augmented with the clandestine importation of nuclear-related technologies. All of the proliferating States have set up their nuclear weapons programs combining domestic efforts with imported technologies and expertise. The best example of the latter is the transfer of expertise to Pakistan by Dr. Khan. The effectiveness of this path to the development of nuclear weapons has been influenced by two major factors, level of technological development and level of determination to build nuclear weapons.

South Africa was subject to trade restrictions on nuclear-related technologies. In spite of such embargo, it built its nuclear weapons in a relatively short period of time, less than ten years, because it possessed two important ingredients, raw material and scientific and technological strength. Similarly, the nuclear program of Israel started with imported assistance from France and the United States. It expanded relying on the combination of domestic scientific expertise and technological development. It remains active because the State has determined that it is in its national interest to maintain it. On the other hand, Iraq and Libya lacked technological sophistication and attempted to develop it specifically for the nuclear weapons program. After more than a decade of effort, they still were not successful. One can only guess how long it would have taken Iraq and Libya to build a nuclear device had the former not been invaded and the latter not abandoned it.

At the start of their respective nuclear programs, India, Pakistan and the DPRK shared to a large extent the same scientific and technological profile with Libya and Iraq. They also followed a similar path, namely, a combination of imports and domestic development. The length of time it took each of the three States to develop their weapons can be associated with the resources available to each of the three. India tested a nuclear device in 1974 much earlier than either Pakistan or DPRK. While one can surmise that Pakistan had built and stored unassembled nuclear bombs much earlier than the time it conducted the first test, the evidence indicates that it devoted a substantial amount of resources, trade restrictions and embargoes notwithstanding.

While the industrial profile is the primary indicator of the ability of a State to build nuclear devices, it is secondary to the determination of a State to do so as the case of the DPRK illustrates. Taking the beginning of the decade of the nineties as the start of the nuclear program and the test in 2006 as another benchmark, it can be concluded that it took the country more than 15 years to build and test a rudimentary nuclear device. To do so it had to build an indigenous infrastructure for the entire nuclear fuel cycle. One then is led to conclude that if a State determines that it is in its national interest to build a nuclear weapon, it will do so. The length of time it will take from the moment the decision is made until a device is tested is inversely related to the scientific and technological resources available to a State. It will take much shorter if those resources exist, than if they have to be acquired *ab initio*.

4. Indicators of potential proliferators

From the preceding discussion it has become clear that nuclear proliferation has not occurred in a vacuum and is not likely to occur absent a set of conditions that would compel a State to start a covert program and be willing to bear the costs associated with the risk of detection. A State would initiate such a program only after it would determine that possession of nuclear weapons would serve a paramount national interest considering that the costs of such program would be substantial. In all cases discussed in this paper, the proliferating States sought nuclear weapons as a deterrent to threats, real or perceived, from one or more neighboring States. Thus the primary indicator of probable proliferation is the existence of serious and prolonged territorial disputes. A corollary indicator is the existence of substantial military imbalance between the potential adversaries. India started its nuclear weapons program to achieve parity with a nuclear-armed China and Pakistan reacted similarly to achieve parity with India. In the cases of Israel and South Africa, it was the perceived imbalance in the size of the conventional forces that nuclear weapons aimed to correct. In the case of Iraq a case can be made that nuclear weapons were sought either as a deterrent to a nuclear-armed Israel, or as means to gain advantage over its neighbors, or both.

The second conclusion drawn from the cases studies is proliferating States exhibit some degree of militarism. The apartheid regime in South Africa maintained power by force. Israel relies on military force to maintain the Jewish character of the State. The creation of India and Pakistan from the British colonies was accompanied by bloody conflicts that saw the rise of strong military establishments. Pakistan, in contrast to India, saw the rise of a strong and dominant military establishment. Iraq was and the DPRK still is governed by strong dictatorial regimes. Thus, another indicator of probable proliferation is the degree of authoritarian control the government of a State exercises over its population. A corollary indicator is the level of transparency in a State. The probability that a State would proliferate is inversely related to the degree of transparency in that State. In an open society it would be very difficult to maintain for long a clandestine weapons program.

Another indicator can be deduced from the length of time it would take a State to build a nuclear weapon from the moment it decided to do so. The development time is a function of the scientific, technological and economic development of a State. It took South Africa and, presumably, Israel, less time to build their weapons than it has taken the DPRK. One could only guess how long it would have taken Iraq to do it, had it not been forced to dismantle the program. Since the length of time it takes to build a nuclear weapon is inversely related to the degree of scientific, technological and economic development, the time window for detecting it is shorter for technologically advanced States that for States that are at some early stage of development. For long observation periods the safeguards system would have the opportunity to collect and evaluate more data over time. On the other hand, the shorter window of opportunity to detect a nuclear weapons program in a technologically advanced State would make it difficult to collect enough data to detect it with some degree of confidence, raises the question whether such a program is detectable in the first place if the State decides to embark on it. On the other hand, the detection scheme for States with less advanced technological bases would have available more time and larger quantities of noisy data to detect weapons program with the same level of confidence as that for the technologically advanced States. Of course, the technological development of the States subject to safeguards forms a continuum do not fall into two distinct categories of development. Nevertheless, detection of weapons development can start with a two-detector system and evolve into an array of detectors to cover States at various levels of technological development.

Finally, the diverse stages of development raise the question what does one mean by non-compliance [19]. Now that we have compiled a set of indicators that would characterize a State that would likely initiate a nuclear weapons program, we can revisit the question of what does one mean by non-compliance from yet another perspective. There is no credible evidence to indicate that the nuclear weapons programs were detected when the programs were at the planning stage. One should seriously question the view that an effective safeguards system could be designed to detect a weapons development program that exists only on paper. A State with such a program would violate the spirit of the NPT. Nevertheless, if the safeguards system could not detect it, the IAEA would consider the State to be in compliance, because the safeguards system could not detect the non-compliance.

As a practical matter, detection of non-compliance would have to be concentrated at the acquisition phase. As it was previously mentioned, States built nuclear weapons by acquiring domestic research, development, testing and production capabilities. Traditional safeguards by seeking to detect diversion of nuclear fuel, aims to detect non-compliance at the stage of the weapon development process where the nuclear material would be enriched to weapon-grade level for insertion into an existing casing. A State in an advanced stage of technological development with an extensive research, development and manufacturing infrastructure could easily have the parts of one or more bombs assembled and tested minus the nuclear material with minimal probability of being detected. On the other hand, if a State starts from a minimal technological infrastructure on a research and development program for the sole purpose of building nuclear weapons, the import of specialized materials and technologies would be a strong indicator of a clandestine program and a safeguards system could be devised to detect potential non-compliance at a fairly early stage of the program. The same system would not be effective if it were to be applied to a technologically advanced State.

5. An adaptive model for integrated safeguards

The preceding analysis leads to the conclusion traditional and integrated safeguards are fundamentally different concepts. To verify the absence of a weapons program in the entire States one must design a system to detect the presence of specified and measurable activities. Even so, the examples of proliferation discussed in this paper illustrate the practical impossibility of doing so. Iraq's program was detected only after a military seize.

A safeguards system monitoring an ill-defined process, i.e., a "State as a whole" and lacking a precise definition of prohibited activities, i.e., unambiguous definition of non-compliance, can only generate ambiguous and imprecise results. Given the existence of these ambiguities, the challenge for the IAEA is to device a safeguards system that would minimize the uncertainty of detection of clandestine nuclear weapons program. As it has been shown, States embark on the development of nuclear weapons in the presence of certain conditions making proliferation a Markov process. Consequently, an effective detector of proliferation must take into account the likelihood of proliferation. In this paper we have identified a set of conditions that would increase the likelihood of proliferation.

This observation points to the need for an *adaptive safeguards* system. It would be conditioned upon the likelihood of the existence of a clandestine program and upon its characteristics. At one end of the scale, the likelihood would be high for regions that have the following characteristics: neighboring States are in unresolved conflicts involving territorial disputes, the political systems exhibit various degrees of authoritarianism and lack of transparency, the technological infrastructures tend to be weak. The smallest likelihood would be for those regions with the following characteristics: there are no major territorial conflicts between neighboring States, the political systems are democratic with relatively high levels of transparency, and have advanced scientific and technological infrastructures. The relationships between the primary indicators and the likelihood of proliferation are shown in Figure 1. Since the empirical data are scarce, the functional relationships are indicative. The combination of the four indicators yields a single measure of the likelihood of the existence of a clandestine program as

$$\begin{aligned}\Pr\{prolf\} = {} & \Pr\{profl \mid cnfl\}\cdot\Pr\{cnfl\}\\ & +\Pr\{profl \mid mltr\}\cdot\Pr\{mltr\}\\ & +\Pr\{profl \mid transp\}\cdot\Pr\{transp\}]\\ & +\Pr\{profl \mid tecndev\}\cdot\Pr\{tecndev\}]\end{aligned}$$

If a State is highly likely to have a clandestine program would have started it on the basis of the military significance of the weapons or on some concept of psychological warfare. Since the time it takes to develop and test

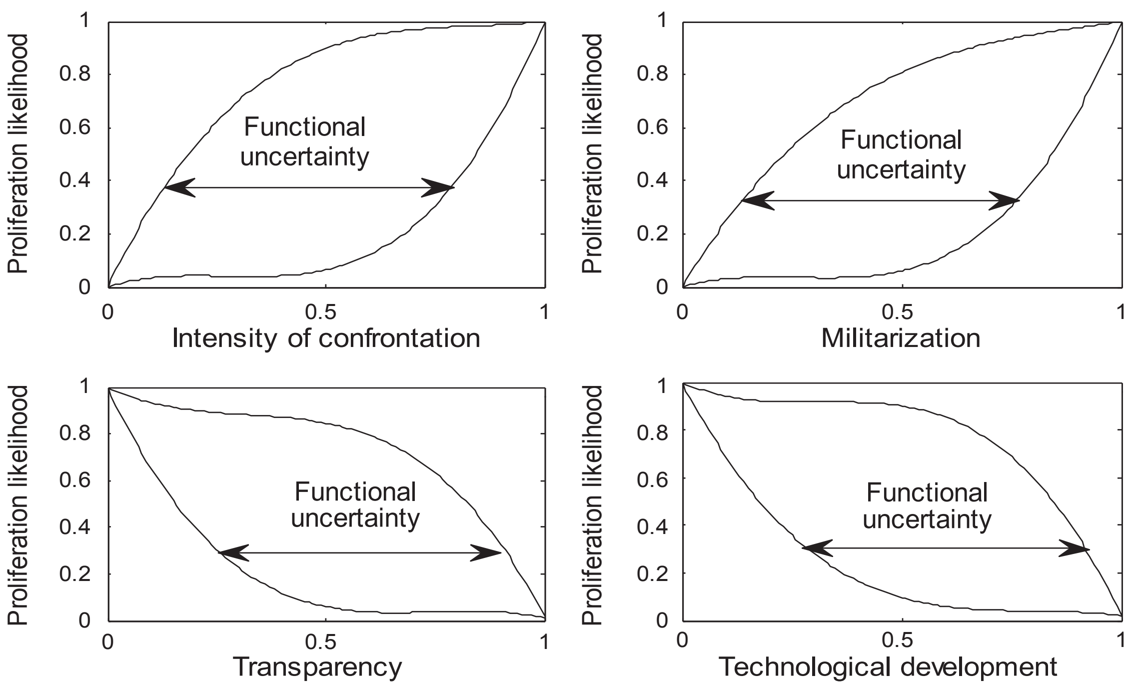

Figure 1: The likelihood of the existence of a clandestine nuclear weapons program as a function of the characteristics of a particular State

a rudimentary nuclear device is more than 10-15 years, the safeguards systems has more than enough time to collect and integrate relatively weak indicators over long time intervals. As the cases of Libya and Pakistan have illustrated, the safeguards system would need to be able to monitor the imports of technology that is primarily applicable to some part of the fuel cycle. An extension of the model would be to take into account the impact of sanctions on the development of nuclear weapons. The argument in favor of sanctions is that they deprive the State suspected of developing nuclear weapons of the necessary technology and materials that are not available domestically. On the other hand, sanctions on a State determined to acquire these weapons, provide the impetus for the development of indigenous technological capabilities. All the case studies have shown that sanctions, at best, delay but do not stop nuclear proliferation. The challenge for the safeguards system is to assess the impact of restricting trade on the probability of detecting clandestine weapons programs in States that are highly likely to have such programs.

At the other end of the likelihood range, the decision to acquire nuclear weapons would be conditioned on different criteria. These are hypothetical because there has been no such case in the history of the NPT. If a State in this group decides to acquire nuclear weapons, it would have to do so if suspects that an existential threat might develop in the relatively near future for which nuclear deterrence would be a strong option. In that case, it would seek to acquire a substantial stockpile requiring the diversion of a substantial amount of nuclear material. Thus, for this group of States, the aim of the Integrated Safeguards would be to detect diversion of substantial quantities of nuclear material within a short time interval. This would be in contrast to the objective of the classical safeguards that aims to detective diversion of small quantities over long time periods. It would not be in the interest of a State belonging to that group to divert small amounts, because the material would not be of any practical use given the conditions under which the State decided to build nuclear weapons.

6. Conclusions

On the basis of the analysis presented in this paper, it can be concluded that not all States under IAEA safeguards are equally likely to become nuclear proliferators. The likelihood of a State deciding to develop nuclear weapons is conditioned on the presence of a set of identifiable conditions that would cause a State to undertake such a program. These conditions are directly related to the existence of unresolved conflicts in a region, repressive and non-transparent political systems and level of technological and economic development. For Integrated Safeguards to verify the completeness of the declaration of a State, it needs to devise a decision mechanism that would be able to detect the presence of a clandestine program using incomplete and ambiguous data. In other words a maximum likelihood estimator is needed that computes likelihood ratios on the basis of the indicators of the likely proliferators. Since conditions on the globe are not static, the detector must be flexible to accommodate the changing conditions leading to the concept of adaptive safeguards.

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Exploiting the Geospatial Dimension of Data in Support of IAEA Safeguard

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Abstract

The nuclear fuel cycle is highly dependent upon geographic factors and each step in a state's nuclear fuel cycle occurs in geographically explicit locations. Because of this, information indicative of these activities is likely to have a strong geographic competent. Therefore, it is suggested that open source information management in support of State Level Assessments also be geographically focused. With an explicit geographic interface for collecting, evaluating, analyzing, structuring, and disseminating open-source information, the information management challenges faced by the IAEA can be made more intuitive and result in more effective, information-driven safeguards analyses, potentially leading to more timely safeguards conclusions. This paper proposes an information management framework based upon geographic information systems (GIS) principles for open-source information analysis in support of international safeguards.

Keywords: Safeguards; geospatial; open sources; information management; analysis.

1. Introduction

The IAEA is chartered with providing the international community credible assurance of the absence of undeclared nuclear activities within states with an Additional Protocol (AP) agreement in force. To do this, the IAEA not only verifies the correctness of state declarations based upon material accountancy, but also analyzes available information sources, including open sources, in order to draw safeguards conclusions for each state. While highly effective, this information driven safeguards approach places greater burden on the resource of an already lean safeguards system. Assuming that each of 65 states estimated by the IAEA to be considering developing nuclear energy capabilities in the future [1] will enter in AP agreements, the evolving safeguards system must include new efficiencies in order to maintain effectiveness as safeguards workload increases significantly.

In order to ensure that safeguards practices maintain effectiveness in the face of continuing resource constraints, the agency has developed a research and development program aimed at evolving the most efficient safeguards verification regime possible [2]. This program stresses heavily the need for an integrated information management architecture for collecting, evaluating, structuring, analyzing, securing, and disseminating all available safeguards-relevant information. Because the nuclear fuel cycle is highly geographic in nature, the information indicative of fuel cycle activities is likely to include a high degree of geographic content. For example, uranium and thorium ores are not uniformly distributed across the Earth's surface; surface mines have generally recognizable geographic footprints and extents; milling facilities tend to be co-located with mines; enrichment reactors must be located near bodies of water; many nuclear material handling facilities such as centrifuge facilities tend to be located far from major population centers but have intensive infrastructures; nuclear materials are transported on geographic networks; and so on. We suggest, then, that by developing a safeguards information management system with an explicit geospatial focus and toolset, there exists the potential to increase the quality of analyses while decreasing the time required.

In addition to realizing new efficiencies, information driven safeguards requires the IAEA to assess a broader range of information sources, to include open source information, and third party information [3]. This information is combined with information from in-field verification activities and analyzed to ensure they are consistent with state declared information. The collection and analysis of open-source information will continue to play an essential role within the strengthened safeguards regime. Because a great deal of open-source information is unstructured and heterogeneous, such information can be more efficiently identified, collected, and structured based upon this geospatial dimension. Further, as noted above, nuclear fuel cycle activities occur in geospatially explicit locations, and open-source information indicative of these activities are likely to have a strong geospatial component. Therefore, by exploiting the geospatial component, information gathering and analysis can be integrated at the state level with other information more readily.

Geospatial information in the form of commercial satellite imagery has been used with great success in safeguards work for more than a decade [4]. Recently, the IAEA has realized the potential of geospatial information more generally as evidenced by the investment in a geospatial exploitation system, intended to streamline the sharing of geospatial information across departmental lines [2]. This work, however, proposes an integrated information management framework based upon GIS principles and tools that will allow analysts to more efficiently detect, extract, analyze and share safeguards-relevant open source information by exploiting the geospatial dimensions of this information.

Recent progress in GIS development is allowing developers to create custom tools that have the potential to provide analysts with little or no GIS experience the powerful capabilities of geospatial analysis. One of the goals of this research is to develop an analyst-centric framework and toolset for analysts to generate safeguards-relevant geospatial assets based upon structured and unstructured open source information in support of their expanding safeguards responsibilities. The authors have surveyed a number of open-source geospatial technologies that can provide analysts with this essential GIS functionality.

This geospatial framework can be further expanded to incorporate all safeguards relevant information—from state declarations, in-field verification activities, as well as open-source analysis—in order to provide a fully integrated, state-level information architecture based on GIS principles.

2. Geospatial Information for Safeguards

Safeguards-relevant geospatial information might include aerial and satellite imagery, reference maps, detailed site information, terrain models, and digital geographic feature datasets. Recently, however, there has been a marked increase in what one might call non-traditional geographic information available from open sources. Traditionally, geospatial data have come in two primary types, each with relatively few but well defined file formats: vector (or geometric) and raster (or image) data types. While this distinction still holds in general, the emergence of collaborative web technologies has supported the rise of dozens of new ways of encoding geospatial data, as well as a shift in the ways in which geospatial data is produced and conceptualized. Through the emergence of location-based services and web-based social networking technologies, user-generated content containing geospatial information, termed volunteered geographic information (VGI) [5], has become a ubiquitous part of the digital information landscape. These data vary from geotagged images and geographically referenced microblog posts to place name references in unstructured text and aerial images in media reports. This “citizens as sensors” phenomenon has been exploited aggressively by emergency response, humanitarian aid and human rights organizations, among others [6]. Mobile and location-based technologies allow VGI to exhibit extensive global coverage with potentially high locational accuracy, and are generated in rapid response to events. However, because these data are heterogeneous and unstructured, the systematic collection and analyses of these data required specialized software tools.

3. Geospatial Tools for Safeguards

The effective use of open-source information requires an integrated system for collecting, evaluating, structuring, analyzing, securing, and disseminating information [7]; however, working with geographic information, and particularly unstructured geographic information, requires a distinct and diverse set of tools. Generally, proprietary software for working with geospatial information is costly and requires extensive training. Moreover, proprietary software rarely accommodates the level of customization required to integrate different tools. However, there is a large community of software developers working on open-source geospatial technologies. From these technologies a geospatial analysis toolset can be constructed that allows analysts to extract and analyze geospatial information, a task once reserved for highly trained staff. In the following paragraphs, we discuss several of these open source tools. Note that the technologies mentioned here are not intended to be an exhaustive list but rather an overview of some of the most widely used and available products.

3.1. Collect

Because the workflow of safeguards analysis has a clear correspondence to the research process in which references are collected, tracked, and organized, and reports are generated, reference management tools can be highly effective analyst tools. Reference management software is used to collect, store, organize, and share electronic research sources. While there are several free and open source reference management systems, Zotero,[1] developed by George Mason University is deployed as an add-on for the Firefox web browser and therefore integrates easily into the analysis workflow. Zotero detects and extracts item metadata in a variety of formats from websites and automates many tasks such as text citation and bibliography generation. Additionally, Zotero can be extended to detect other data formats, including structured geospatial data formats, through the development of translators that detect specific patterns within web pages and save data in structured manners.

To fully automate the process of geographic data collection the use of web crawlers can be employed. Web crawlers are computer programs that traverse the Internet through linked web pages, can be trained to recognize key words or data types, and can extract entire web sites or specific information. Dozens of open source web crawlers exist that can be tailored to specific tasks. [2]

1 http://www.zotero.org/
2 For a discussion of web crawling see: J. Cho, Web Crawling Project, http://oak.cs.ucla.edu/~cho/research/crawl.html

3.2. Structure

The majority of geographically referenced information in open sources is unstructured and heterogeneous. In order to make this information usable in an integrated system, the information must be converted to a common or interoperable format. To achieve this it is necessary to develop and apply a standardized definition of terms and relationships. Ontologies, formal specifications of terms and their relationships within a given knowledge domain [8], allow for the standardization of heterogeneous and unstructured data by defining the spatial, temporal, and thematic dimensions of the data. By applying computer-readable metadata based on these ontologies (that is, semantic mark-up), it is possible to further automate detection and processing of these data by allowing computational reasoning about the geospatial and thematic relationships among the data elements.

For this project, several ontologies are likely needed. First, a geospatial ontology will be required to define types of geospatial entities, for example, administrative districts, natural features, etc.,[3] as well as geospatial relationships, for example, adjacency, proximity, containment, etc.[4] Second, a geographic place names ontology will be necessary to standardize the identification of named geographic entities. Several existing place name ontologies exist in the form of online gazetteers, including GeoNames[5] and Yahoo! GeoPlanet[6]. Finally, thematic or domain ontologies are needed to define safeguards relevant terms and relationships. Examples might include ontologies for the nuclear fuel cycle and nuclear reactor or centrifuge facility operations. Domain ontologies are often specified using Web Ontology Language (OWL) definitions.[7]

Existing implementations of the semantic web, which seeks to supplement web resources with computer readable metadata, can support these functions, though the adaptation of these standards has only occurred within relatively narrow parts of the Internet. The utilization of ontologies to increase the effectiveness of safeguards activities has been explored [9], although not within a geospatial context.

3.3. Analyze

Once geospatial information has been collected and structured, there are a number of open source tools available to analyze these data. GeoTools[8] is a Java-based open source geospatial library that permits geospatial operations, such as buffering or distance and area calculation, and spatial queries.

An important analysis capability due to the volume and complexity of the information gathered by safeguards analysts is that of entity extraction [10]. This is an automated process by which unstructured text is analyzed and tagged according to the type of entities it contains for example, people, places, companies, etc. There are a number of open-source entity extraction tools currently under development. The Unstructured Information Management Architecture (UIMA) project,[9] which is under development by the Apache Foundation, is a server-side application that, among other things, has entity extraction capabilities. Alternatively, Yahoo! PlaceMaker[10] is a free web service that extracts place names from text (a process known as geoparsing) and returns metadata for the document including geographic scope and coordinates.

GeoNames is a place-name database, or gazetteer, amassed from dozens of sources including user contributions. While it provides free access via an application programming interface (API) it can also be downloaded for local use. Because GeoNames is semantically enabled, it has the ability to conduct automated spatial reasoning such as adjacency, containment and proximity. Though not necessarily open source, web services can provide important analysis capabilities and can generally be accessed at no cost.

The ability to visualize information on a map provides a number of powerful analysis capabilities. OpenLayers[11] is a pure JavaScript library for displaying and manipulating geospatial data within a web browser. The ability to display published geospatial resources from anywhere on the internet, including commercially available base maps from providers such as Google, Bing, Yahoo!, NASA and others, makes OpenLayers an excellent candidate for the front-end interface of a geospatial safeguards tool.

Each of these geospatial tools adheres to international standards for interoperability set forth by the Open Geospatial Consortium[12] and are compatible with a large number of both open-source and proprietary systems and data types, including ESRI's ArcGIS[13] products.

3.4. Disseminate

The sharing of information within the organization is an essential requirement for effective safeguards analysis. Content management systems (CMS) allow for a large number of users to contribute to and share stored data by controlling access, aiding in storage and retrieval, and providing a collaborative web-based environment and common information architecture. In a CMS, data can be defined very broadly as binary objects: documents, images, scientific

3 http://www.w3.org/2005/Incubator/geo/XGR-geo/
4 http://data.ordnancesurvey.co.uk/ontology/ spatialrelations/
5 http://www.geonames.org/
6 http://developer.yahoo.com/geo/geoplanet/
7 http://www.w3.org/TR/owl-features/
8 http://www.geotools.org/
9 http://uima.apache.org/index.html
10 http://developer.yahoo.com/geo/placemaker/
11 http://openlayers.org/
12 http://www.opengeospatial.org/
13 http://www.esri.com/software/arcgis/

data, etc. Workflow and version control are two of the primary advantages of a CMS. Plone[14] is one open source CMS built on a Python platform that is known for excellent security. Other widely used, open source CMS include Drupal[15] and WordPress,[16] both built on PHP. Many CMS can also be extended to handle geospatial information. SharePoint,[17] a popular commercial document management system, is widely used, including at the IAEA. These can be deployed as entry portals to shared safeguards information as has been previously proposed [11].

Several of the tools noted above can also assist in the dissemination of open-source geographic information. For example, Zotero can be configured to automatically synch with internal servers allowing analysts to create and share reference libraries. GeoServer allows users to publish and share maps via web mapping services (WMS), which can in turn be viewed within an OpenLayers mapping interface.

4. Case Study – Paks Nuclear Power Plant

To demonstrate the wide variety of open-source geospatially referenced information available to safeguards analysts, a test case was developed based on a hypothetical need to collect safeguards relevant information to support on-site inspection activities at Paks Nuclear Power Plant (NPP) near Paks, Hungary.

A three phase search strategy was implemented in order to find distinct types of geospatial information.

First, a general Internet search strategy using search engines such as Google, Google Scholar, and Wikipedia leads to the discovery of unstructured geospatial data in text and images. These data require additional computational procedures to transform them into geospatial data types useable in a mapping context.

Second, a geographically enabled search strategy using specific geospatial filters such as coordinate pairs, bounding box coordinates, or administrative boundary names, leads to the discovery of geotagged data and geospatial web services. These data are generally unstructured but have associated geospatial metadata. Examples are geotagged images or blog posts.

Third, structured geospatial data, such as ESRI shapefiles and GeoTIFF images, are discovered through geospatial data portals and clearing houses. In general, these outlets are run by government or not-for-profit agencies.

Note that these search strategies are not mutually exclusive and one search strategy can lead to the discovery of different types of data.

[14] http://plone.org/
[15] http://drupal.org/
[16] http://wordpress.org/
[17] http://sharepoint.microsoft.com/

General Search

The first search included sites such as Google, Google Scholar and Wikipedia. Over 580,000 results were received on Google by searching for “Paks Nuclear Power Plant”. The first entry returned was that of Paks NPP on Wikipedia. The second site listed was the home page of the power plant.

The Wikipedia site for “Paks Nuclear Power Plant” had a wide variety of geographically referenced data [12]:

- Location Maps
- Latitude and longitude coordinates
- Multiple current and historic images of the site
- Links to the Paks NPP website and many other related sites
- Links to other papers and references

The Paks NPP home page [13] in English also provided some geospatially referenced information:

- Address of the facility
- Location map
- Images of the facility within the “Virtual Tour and Gallery Links” section

From these two websites alone, a substantial geospatial reference for the plant can be built. However, note that these data are in text and image formats and thus cannot be easily used by traditional GIS. However, by applying additional computational procedures such as natural language processors to extract place names, these data can be formatted for use in geospatial applications.

Geo-enabled search

From the information gained during the general Internet search, we obtained the geographic coordinates of the Paks NPP (46.5725N, 18.854167E), Google Maps was used to get an aerial image of the site, dated 20 December 2006. Also available in Google Earth are 3-dimensional building renderings, including a photorealistic rendering of buildings at the Paks plant (Figure 1). Google Earth, which has become the lay person’s geographic visualization tool of choice, has the ability to overlay data from dozens of already defined sources including Web Mapping Service (WMS) layers from any external source.

Next, Wikimapia [14], a crowd-sourced mapping service that allows users to digitize and annotate geographic features, was examined. Users have digitized buildings and infrastructure at the site, including reactor housings 1 through 4, cooling water input and output systems, switchyard, control room building, visitors center, fire station, meteorological tower, and bus station, among others. This information can be extracted through Wikimapia’s API in XML, JSON, KML, and binary formats.

Figure 1: 3D, photorealistic rendering of Paks Nuclear Power Plant available from Google Earth.

The third geo-enabled search was through the GeoHack website[15]. GeoHack, a geospatial data portal developed by the Wikimedia community's Toolserver project,[18] aggregates mapping services for georeferenced content from many different sources. By querying a latitude and longitude coordinate pair, GeoHack returns links to various mapping services that display data centered on these coordinates as well as links to other web-based resources related to these coordinates and thus serves as a valuable gateway to a large amount of geospatially referenced data. From here, a large number of other websites containing geo-tagged information were discovered to include:

- 28 global map services sites (Google Maps, Wikimapia, OpenStreetMap, etc.)
- 12 Wikipedia links
- 10 photo hosting websites
- 19 "other sites"
- Over 100 regional map services

While each of these sites are not unique data points, as some links are coincident or contain identical data, this does illustrate the relative ease with which aerial and satellite imagery and geographically referenced data and visualizations are obtainable.

Structured geospatial data search

Finally, an Internet search was conducted for standard, structured geospatial data such as ESRI Shapefiles, digital elevation models (DEM), and GeoTIFF images. Effective use of data in most of these formats requires specialized GIS software (for example, ArcGIS or MapInfo) and a trained geospatial specialist. However, several XML-based geodata formats (for example, KML and GML) have emerged in recent years that allow these data to be used within a web-based computing framework and available to a larger number of analysts.

The quality and resolution of the GIS data discovered for the Paks NPP site ranged from very little to extremely high. While a large amount of data were discovered at state and regional scales, very little data were found at local and site-specific scales. For example, geospatial data for Hungary and Hungarian counties were abundant, while data for municipal scales and the Paks NPP site in particular were more difficult to come by. However, what one might consider "micro-level" geodata, such as geotagged photographs, were widely available. This trend might indicate the need to and benefit of examining other sources of geographically referenced data to supplement this mid-scale data void.

Results

Based on discussions with analysts, desirable geospatial information for safeguards and security analysis includes:

- Overhead aerial or satellite imagery
- Reference maps and images to provide context
- Reference information such as roads and other nearby geographic features
- Ground-based photographs
- Detailed site information
- GIS/map data to use in analysis

[18] http://meta.wikimedia.org/wiki/Toolserver

Each of these data types were discovered on the open Internet with relative ease. The GIS/Map data searches yielded information at both a national and regional level and, with sites such as OpenStreet map, relatively accurate street-level data is available. Detailed GIS or CAD data of the Paks NPP site itself was not found.

Effective use of these data for analysis requires specialized training and expensive software tools that may not be widely available to analysts. Also, notably missing from this list are unstructured data (such as text data) containing geospatial references. Because these data are not easily used in a geospatial framework they are often ignored or overlooked.

5. Discussion and Conclusion

Using a phased search strategy that includes a general Internet search, geospatially-enabled search, and structured GIS data search, it is possible to assemble a basic geographically referenced set of data without a specialized GIS analyst or expensive GIS software.

The Additional Protocol presents challenges to safeguards analysts by increasing the breadth and depth of information sources that could be examined. As the number of State-level evaluations that the IAEA performs continues to grow, the need for increasingly effective information retrieval and knowledge management tools will also grow. As the expanded mission continues to stretch valued resources, additional efficiencies must be identified and exploited so that the IAEA can continue to provide meaningful assurance of the peaceful use of nuclear activities.

Making use of the geospatial dimensions of information can increase the efficacy of open-source information analysis. In order to do this, an integrated system to collect, structure, analyze, and disseminate safeguards relevant information must be crafted in such a way that it aids and does not impede the job of the analyst. The use of open source technology to carry out these tasks represents a possible method for gaining this enhanced ability.

Because of the ease of use and low life-cycle costs, the use of these open-source tools to create a basic geospatially referenced data set has the potential to increase the use of geospatially referenced data in future safeguards analysis. When configured to work within an existing safeguards analysis workflow, these tools can allow analysts to leverage both structured and unstructured geospatial data from the open Internet, a capability that generally is available only to those with specialized training and expensive, proprietary tools.

Several no-cost, open-source tools exist that lend themselves to further development for use in safeguards specific analysis. Zotero, an open-source reference management tool, for example, has the ability to produce maps from place names in web-based collections of documents in seconds rather than the hours or days when compared to traditional GIS tools, all the while extracting, storing, and organizing references in a structured manner. OpenLayers and GeoServer are open-source projects that allow for the handling, visualization, and sharing of geospatial data.

In order for the efficient use of this heterogeneous and unstructured geographically referenced material, more work needs to be done to create standardized and automated processes for discovering, integrating and organizing the data. Development and application of ontologies and semantic technologies will be necessary to achieve this goal.

Finally, while open-source data can be an important supply of new types of information for safeguards analysis, it must be approached with some caution. Open-source data, especially crowd-sourced information, can be inaccurate, incomplete, biased or even fabricated [16]. A future goal of this research is to develop tools and methodologies that provide safeguards analysts the ability to differentiate valid and reliable geospatial data from those data that cannot be trusted.

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Applicability of the Directed Graph Methodology

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Abstract:

Possible methods to construct, visualize and analyse the "map" of the State's nuclear infrastructure based on different directed graph approaches are proposed. The transportation and the flow network models are described in detail. The use of the possible evaluation methodologies and the use of available software tools to construct and maintain the nuclear "map" using pre-defined standard building blocks (nuclear facilities) are introduced and discussed.

Keywords: acquisition path analysis; directed graph; shortest path algorithm; State level approach; transport model; material flow network model

1. Introduction

The State-level approach to IAEA safeguards requires the detailed knowledge and objective evaluation of a State's nuclear infrastructure, including human and economical resources. One possible outcome of such an evaluation is the possible nuclear material diversion roots or paths required for the acquisition of the first nuclear weapon or nuclear explosive device. The technical basis of the evaluation is the physical model of the nuclear fuel cycle, which was developed by the IAEA [1].

Recently (in 2010) the IAEA requested Member State support in the development of acquisition path analysis methodology and applicable software tools. In response to the request, the paper discusses the possible use of two different analytical approaches based on graph models: the shortest path algorithm applied to a transportation type model and the material flow network. Both models are discussed in three different levels.

2. Modelling approaches

Both models are based on a network. A network might be defined as any system of interconnected linear features. A network can be composed of nodes and links between the nodes (edges). In mathematical sense these types of networks are called "graphs" that are mathematical structures used to model pair wise relations between objects from a certain collection. A graph may be undirected, meaning that there is no distinction between the two vertices associated with each edge, or its edges may be directed from one vertex to another.

The processes in a nuclear fuel cycle are either irreversible ones (e.g. irradiation of fuel elements in a reactor) or directed in practice (conversion of materials). Therefore, the two modelling approaches proposed in this paper are directed graph models.

2.1. Acquisition Path Analysis and the Shortest Path Problem (Transport modelling)

In graph theory, the shortest path problem is the problem of finding the shortest path between two selected nodes – the source and the destination – of the graph in such a way that the length of the path – the sum of the weights assigned to the edges belonging to the path – is the shortest of all existing paths [2]. The length of this shortest path is called the distance of the two nodes.

The problem has several forms which are various generalizations of the simple case. These are as follows (including the basic case):

- "single-pair problem": in this basic case as described above, the task is to find the shortest path connecting a selected pair of nodes, the source and the destination;
- "single-source problem": here a single source is selected and the shortest paths from a the source to all other nodes (as destinations) are to be found;
- "single-destination problem": the reverse of the "single-source problem", to find the shortest paths from all nodes as sources to a selected destination (this is identical to a "single-source problem" where the source is replaced with the destination and the edges are reversed);
- "all-pairs problem": in this "full" version of the problem the shortest path between all (connected) pairs of nodes have to be found (obviously, the solutions of the three previous cases are a subset of the solutions of the "full" analysis).

There are various well documented algorithms for the solution of all four types of problems[1]. Without going into the computational details, it is worth to note, that the required

[1] The simplest algorithm for the solution of the "single-pair" and "single source/destination" problem is Dijkstra's algorithm. Any single-pair algorithm can be used for the solution of the generalized cases by simply running the "single-pair" algorithm for all selected pairs. However, more efficient algorithms were developed for the solution of the "single source/destination problem" (e.g. the Bellman-Ford algorithm) and of the "all-pairs problem" (e.g. the Floyd-Warshall or the Johnson algorithm).

computation time is a polynomial function of the number of nodes and edges, i.e. the algorithms are efficient and large complex graphs with thousands of nodes and edges can be analysed without computational difficulty.

A simple – and probably the best known – application of the "single-pair" shortest path problem can be found in the various existing route planning software programs. Here the task is to find the shortest way on a map from one town (or in general from a geographical location) to another. Here the graph is the map with the towns (locations) as nodes and the roads connecting the towns being the edges. If the weights of the edges are the physical lengths of the connecting roads, the resulting distance is the physical distance of the locations along the real road. However, the weights might be assigned different values: time needed to cover the segment of the road, the cost of fuel consumed plus road toll, etc., or a suitable combination of these. Consequently the resulting shortest path solution might in reality be the quickest or the cheapest way to get from one location to the other or an optimal route based on a combination of the features taken into consideration in the computation of the weights. Furthermore, in a route planning application one can select what kinds of roads (motor way, country road, bridge, ferry) to use or not to use (in general: to set an order of preference of these) and what towns to visit or to avoid. As clearly seen on the example of the route planning applications, the shortest path approach offers a great flexibility of analysing complex graphs of thousands of nodes and edges (towns and roads on the map) from different points of view, depending on how the weights assigned to the edges are defined.

Using the analogy of route planning, if the nuclear fuel cycle is described as a map (graph, flow-chart, process-diagram), the acquisition path analysis task can be formulated as a shortest path problem, where the nodes are the different stages of the fuel cycle (facility types, material types), the edges describe possible transitions between them, and the destination is the nuclear weapon (actually, there are three separate destinations which give rise to three, independent problems: one for the ^{235}U bomb, one for the Pu bomb and the third one for the ^{233}U bomb.

Running a "single-pair" shortest path algorithm between any selected node and the destination will give the optimal sequence of steps from that node (stage of the fuel cycle) to reach the destination (nuclear weapon) and establish the lower bound on the length, i.e. the distance. Similarly, running a "single-destination" algorithm for the same graph will provide the results for all nodes as source points in one go. Of course the meaning of the distance will depend on how the weights of the edges are assigned.

2.2. Material flow network modelling

Another way of representing the nuclear profile of a State is to model the theoretical performance capacity of its nuclear infrastructure by the possible ways of producing nuclear materials suitable for manufacturing a weapon from nuclear and other materials at its disposal. This approach can be formulated via a flow network model.

Materials in different chemical and physical form can flow through pipes representing actual processes in the nuclear fuel cycle. Any material flowing through the network can only change its state and quantity by passing through one of the pipes. A given pipe corresponds to an actual process in a given facility type having specific input and output material type. The length of a pipe represents the time needed to process a unit mass of the input material, while the cross section of the pipe scales with the capacity of the process. Import and export of materials can also be taken into account by pipes. A state parameter having value between 0 > – 1 is also assigned to each pipe giving the probability (or possibility) of the existence of the process. A pipe in state 1 is a declared process, while in state 0.1 is an undeclared process which exists with a probability of 0.1.

Each node of the network represents the amount of a material type in a given chemical and physical form present in the State. A node can be composed of sub-nodes representing sub-amounts of material that is actually in the same physical place in a State if needed, but this is irrelevant from the state level evaluation point of view.

As an illustration, two possible pipes are shown in Fig 1., while a possible subset of a flow network is illustrated in Fig. 2.

In Fig. 1 the left pipe represent a gas centrifuge enrichment process with natural UF_6 gas as input and low enriched UF_6 as output, with technical details as declared and verified. The right pipe is an undeclared reprocessing process based on solvent extraction with irradiated MOX fuel as input and separated PuO_2 as output with existence probability of 0.1 that is based on the presence of weak indicators of the process.

In Fig. 2, seven nodes and seven processes are indicated representing a frontend part of the material flow network of the fuel cycle.

The material flow network model can be mathematically described as a finite directed graph G(V,E) with every edge (pipe) $p(i,j)$ having positive capacity (non-zero cross section), finite length and positive state parameter with maximum value of 1. An edge $p(i,j)$ usually connects two different nodes i and $j \in V$ (a pipe processing material i into j with a given flow and capacity). An edge however can also connect i to i. In this case the edge represents an outside source or sink of material i (import or export for instance). There are target nodes $t \in V$ in the network as elements of a set of nodes $t \in V$, representing weapons grade materials.

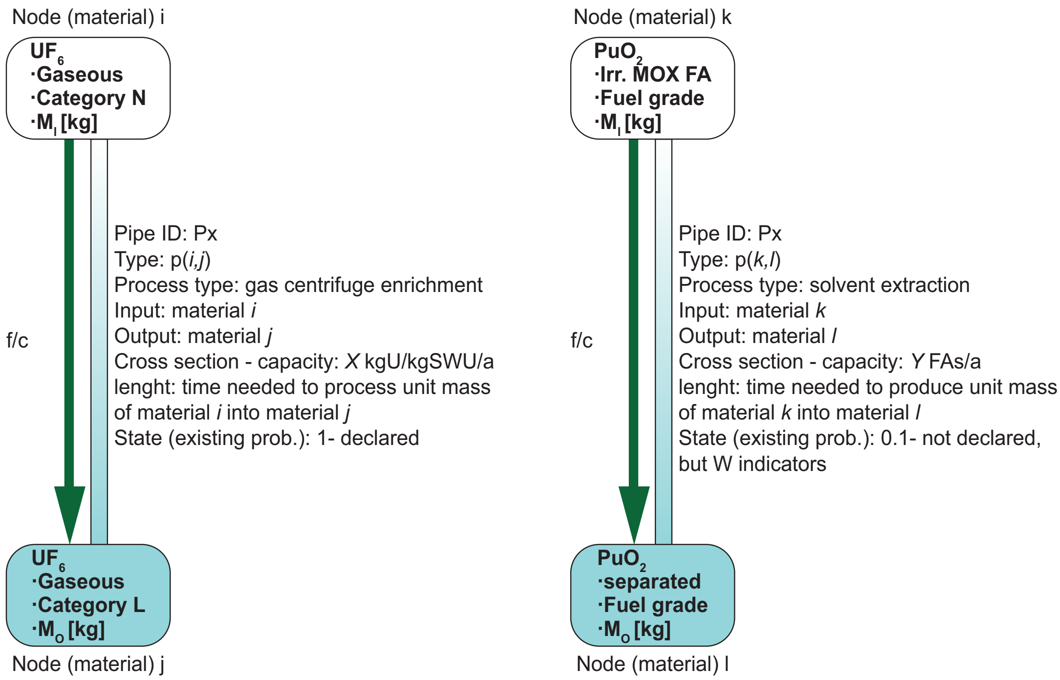

Figure 1: illustrative elements of a flow network of a State's nuclear capacity

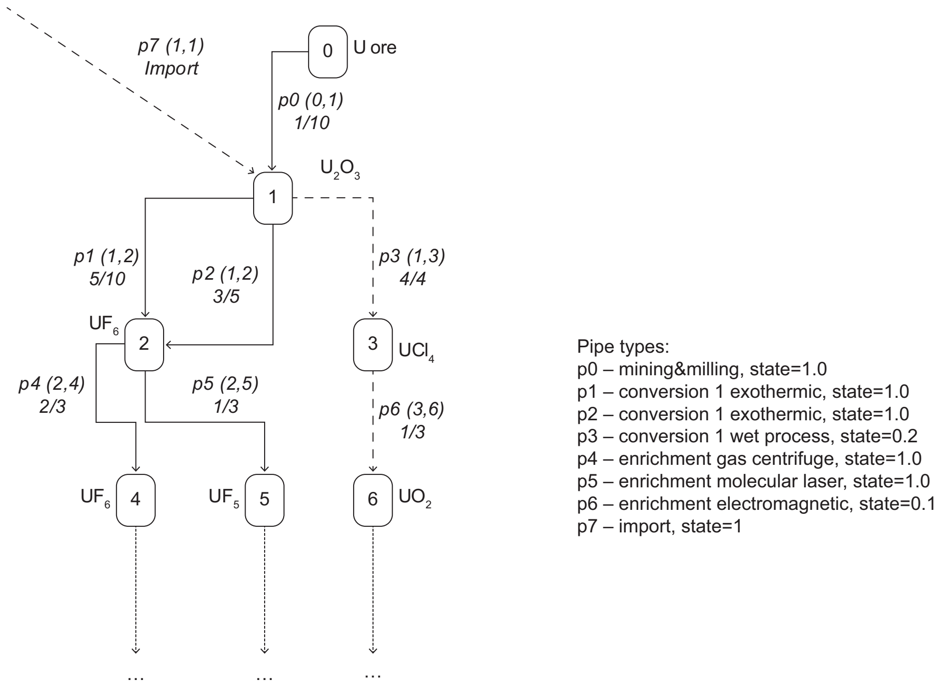

Figure 2: Possible subset of a material flow network

A path $P(s,t)$ in the network connecting a non target node s to target node t exists if there are successive edges starting from s and leading to t with positive flow. Similarly to the state value of the edges, a path can have a probability < 1, if it contains edges with a probability < 1.

There are several possibilities to formulate a problem to be solved on this type of flow network. The most obvious one would be to find all the possible paths in the network that can lead to target nodes of interest starting from any selected non-target nodes (acquisition path determination). The different paths can be ranked according to their probability, length, amount of flow, etc. or the combination of these values. As a consequence there is a great variety of target functions and evaluation methodologies that could be applied to this model. For example well established mathematical formulation and algorithms can be adapted from solutions of the maximum flow problem of multiple source multiple sink flow networks [3], or the algorithms mentioned in the previous chapter [2].

In addition the model can be extended with the introduction of the actual flow/capacity ratio (f/c) parameters as flow control valves applied to the edges. In this way the decision of the proliferator to change the actual flow of the processes can also be modelled (by changing the f/c value of an edge). Alternatively the similar set of parameters can be used to model the efficiency of the safeguards measures applied to a given process (f/c would be then derived from the detection probability of inspections).

3. Proliferation models

In order to use the transportation or the material flow model for acquisition path analysis, the relevant stages and processes of the nuclear fuel cycle – from the uranium mine to the weaponization of HEU or separated Pu – should be represented as a directed graph similarly to the Physical Model developed by the IAEA as illustrated in Fig. 3.

In the following sections the application of the directed graph approach for three different levels (generic, state and facility level) are discussed in more detail.

3.1. Generic Proliferation Model

In the generic model the nodes are simply the various stages of the fuel cycle and the edges are the possible connections. For the purposes of analysis the directed graph can be described with two different types of data sets: matrix representation or adjacency list. In the matrix representation, the cell in row *i* and column *j* has the distance of node *j* from node *i* if node *i* is directly connected to node *j* and is blank otherwise (Fig. 4a). The adjacency list is a simple list of all edges ant their weights in the form (starting node - ending node; distance) (Fig. 4b).

Obviously, Fig. 4 is a very simplistic description of the fuel cycle and its “analysis” leads to a trivial result. (It is like a map of Europe with only the capital cities displayed on it.) But – using the analogy of road maps – it is pretty straightforward how to make the graph of the nuclear fuel cycle richer in detail, more sophisticated, more realistic.

The first step is to look into the more detailed internal structure of the nodes. The same way as a town’s internal street structure can be incorporated into a route planning application without a major effect on the town’s connectivity to other towns, the various major stages of the fuel cycle can be easily enriched in detail. E.g. mining may have different forms (open pit, underground, in situ leach, uranium extraction for coal ash or sea water) or enrichment can be broken up into various technologies (diffusion, centrifuge, electromagnetic, laser, chemical). However, mining products always go to ore concentration plants and all enrichment facilities receive input from conversion. Thus the number of nodes can easily be increased since for each new node only a few new connecting edges have to be defined.

Another analogy of the roadmap that is at hand to use is that nodes and edges may have various attributes. A node can be a settlement (village, town, city), but also a museum or a filling station. An edge might be a motorway, a country road or a city street (with different speed limits) but also a ferry or railway. Also, a road can be an existing one, one under construction or only planned. Based on these attributes different views of the map can be

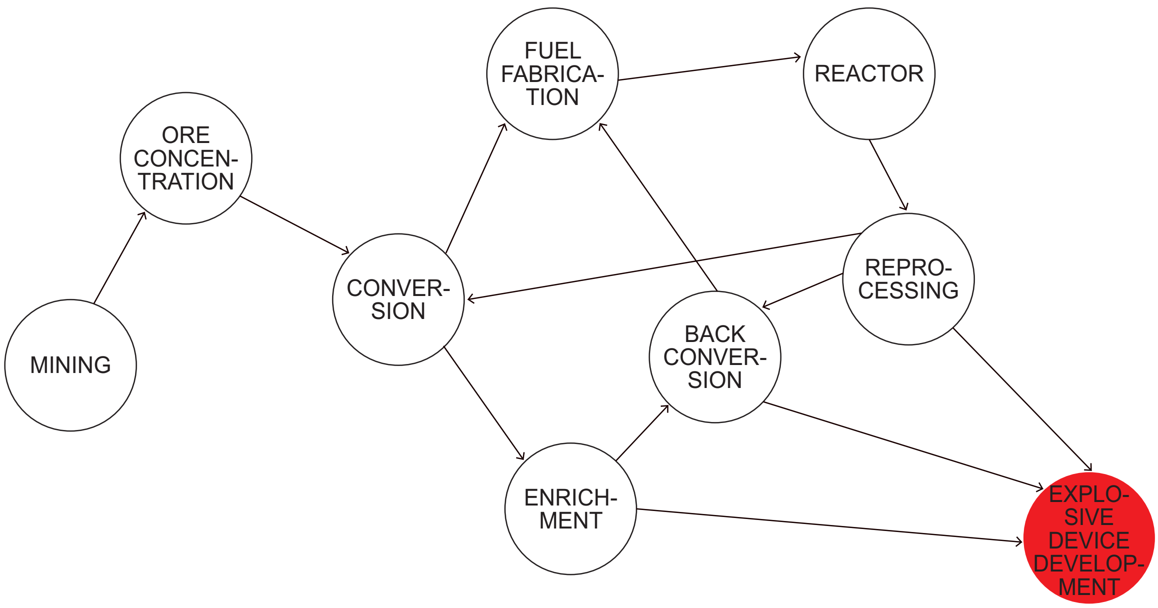

Figure 3: Directed graph illustration of the generic nuclear fuel cycle

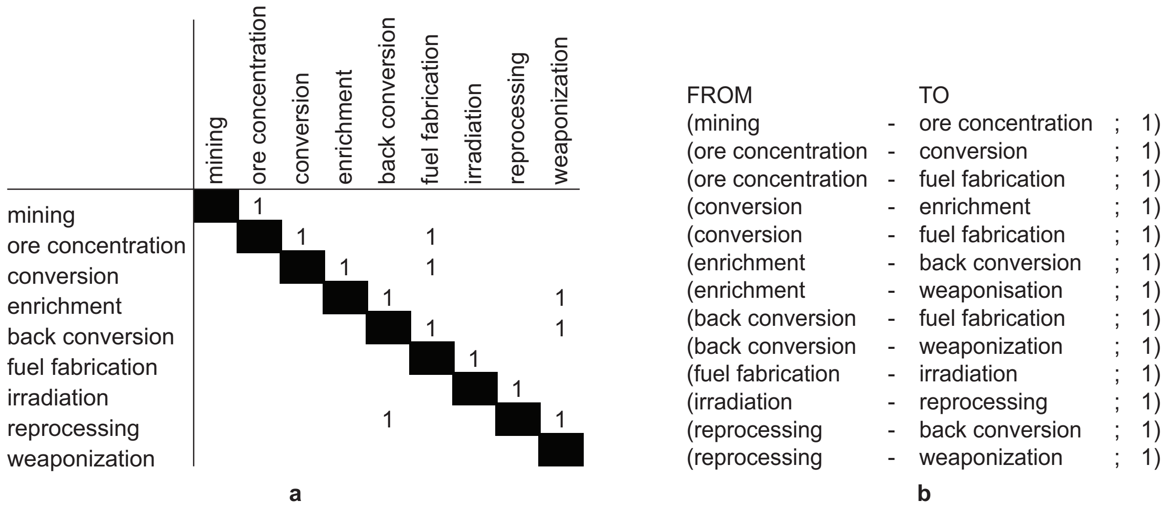

Figure 4: Matrix representation (a) and adjacency list (b) of the generic model shown in Fig. 3.

generated with only those locations and roads that meet preselected criteria. In a similar way, various attributes can be assigned to the nodes and edges of the nuclear fuel cycle graph. For example, a node might be a material type or a process in a facility; a process might require common or high technology (diffusion vs. laser enrichment), might be industrial or in the experimental phase (traditional mining vs. uranium recovery from coal ash or sea water). Other important attributes (declared or clandestine; existing or non-existing; under safeguards or not) can also be added. In such a way, various types of analyses might be run on subsets of the graph meeting different criteria (e.g. only common technology, only declared facilities, etc.).

Finally, the key element: the edges should be assigned a set of quantitative parameters which will then be used to compute their weights and the distances for the shortest path algorithm and other types of analysis. The set of parameters may include the processing time needed to produce 1 effective kg of material, the cost of production, the production capacity or other quantitative data that might be relevant from the proliferation point of view. In general, the weight of an edge can be defined as any computable function of its parameters.

In summary, for the directed graph approach, the creation of the “generic proliferation model” would require the following elements:

- an agreed set of material types and technological processes (nodes of the fuel cycle graph) that describe the current technological possibilities relevant to nuclear weapons acquisition (including processes in experimental phase) in adequate detail (i.e. the matrix of nodes);
- the set of all possible direct routes between materials, processes (edges of the fuel cycle graph) that current technology permits (i.e. the adjacency list or the connectivity matrix);
- an agreed set of attributes to be used for the nodes and edges to facilitate the selection of appropriate subsets of the nuclear fuel cycle graph;
- an agreed set of parameters to be used for quantification of the weights of the edges;
- a set of weight functions to be used for various analyses (e.g. shortest path).

In a shorter, mathematical formulation the generic proliferation model can be fully described with the connectivity matrix ***C****[nodes, nodes, attributes, parameters]* or – equivalently – with the adjacency list ***A****[from node – to node ; {attributes$_m$}; {parameters$_n$}]* and a set of predefined weight functions ***Wi,j***=*{F$_k$(parameters$_{i,j}$)}*.

3.2. The Proliferation Model of a State

Generating the proliferation model of a given State from the generic model is pretty straightforward: one should simply substitute the attributes and parameters of the generic model with State specific values. These State specific values should be derived from the State evaluation process. State specific attributes describe e.g. the existence or non-existence of a given fuel cycle stage in the State (e.g. enrichment or laser enrichment) while State specific parameters are minimum, maximum or average values for the State as a whole (total amount of material, maximum throughput of a process, minimum process time, etc.).

C= *C[nodes, nodes, attributes=State attributes, parameters=State parameters]*
A= *A[from node – to node ; {attributes=State attributes}; {parameters=State parameters}]*
Wi,j=*{F$_k$(parameters$_{i,j}$)}*

Several attributes and parameters have specific significance in the context of the proliferation analysis of a given State. For example, if the attribute describing the existence of a node (a given stage of the fuel cycle) *[exists=yes/no]* are allowed to take a broader set of values *[exists=yes/under construction/planned/no]* and in addition the nodes have a parameter describing the likelihood of their existence in the State *[0<=likelihood<=1; likelihood=0 if exists=no; likelihood=1 if exists=yes]* then the analysis of the existing fuel cycle can be easily amended with taking into consideration possible undeclared materials or processes.

Once the proliferation model of the State has been created (the values of all attributes and parameters has been determined) it is relatively easy to keep it up to date. Attributes need to be modified only when information about the existence of various nodes (fuel cycle stages) changes (e.g. the existence of undeclared laser enrichment). Similarly, parameters need to be re-evaluated only when total inventories of material in the State changes significantly, new facilities are commissioned or shut down, process parameters of existing ones change, or the confidence in the non-existence of undeclared materials or facilities (the likelihood of existence) change.

3.3. The Proliferation Model at the Facility Level

The proliferation model of the State as described above is still a "generic" model in the sense that it represents a summary overview of the State's fuel cycle with general technological capabilities, total capacities etc. without providing a detailed description at the actual facility level. In this chapter we discuss the possibility of using the directed graph approach to develop a detailed realistic representation of the actual fuel cycle facilities and their relationships (connections) within a given State. For this purpose, we again use the road map analogy.

On the road map of a country, a town (node) is represented with the set of roads leading into (entry) and out (exit) of it, and the minimum or typical distances (or travel times) between any pairs of entry and exit points through the town. Similarly we can look at any fuel cycle facility as a node on the fuel cycle graph with a set of defined entry points (various types of nuclear material the facility may receive and process) and exit points (the material types the facility produces) and the set of attributes (technological possibility, capability, declared/undeclared processes) and parameters (process time, capacity, throughput) describing the connectivity of the entry and exit points within the facility. For example a nuclear power plant may receive fresh fuel (declared input) or natural or depleted uranium targets for irradiation (undeclared input) and converts them to spent fuel (declared output) and irradiated targets (undeclared output). The process time and production capacity depends on the design, the thermal power and the operating parameters of the reactor. A low enriched uranium fuel fabrication plant designed to produce LWR oxide fuel from UF_6 normally receives <5% enriched UF_6 and produces UO_2 pellets, fuel rods and assemblies, but may also receive other types of uranium input (oxide powders, >5% enrichment) and may be capable of producing other products than those declared (e.g. depleted or natural uranium targets). Also, any material received at any facility (any input) can simply be shipped out without processing, i.e. all inputs might be directly connected to some outputs. The graph representation of the above examples ("nodes") and their possible connections in the fuel cycle are given in Fig. 5.

Since there are only a limited number of nuclear facility types (fuel fabrication plant, research reactor, NPP, etc.) it is easy to create their corresponding graph and the related connectivity matrices or adjacency lists and use them as building blocks to create the entire graph of the fuel cycle of a given State. If two facilities have the same list of

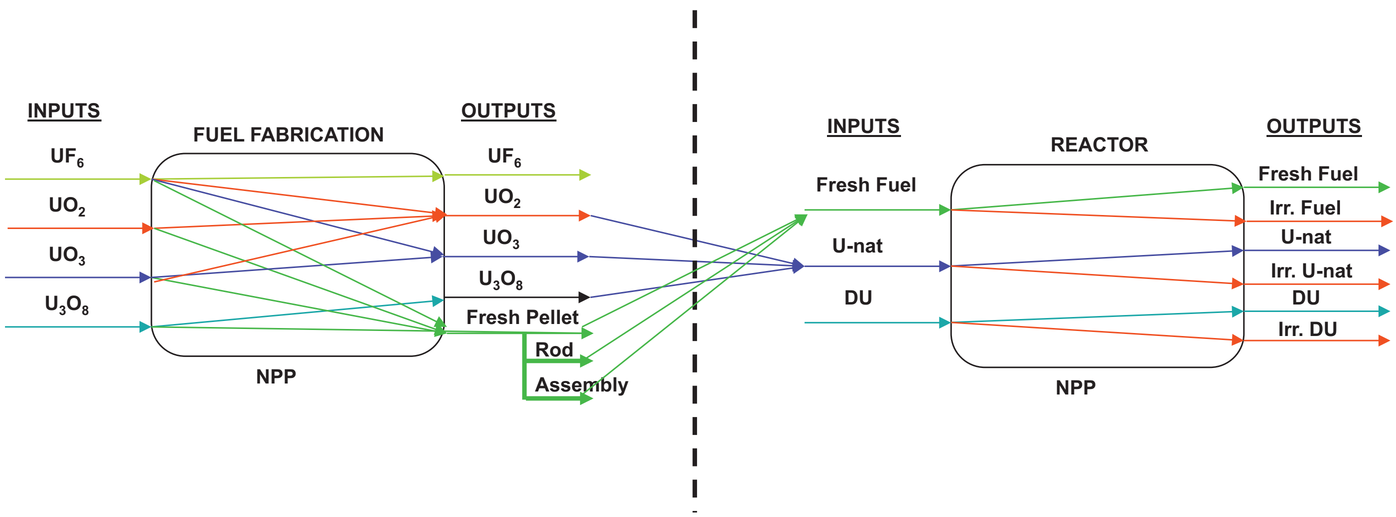

Figure 5: Graphical representation of an NPP, a fuel fabrication plant and their connectivity.

inputs and outputs, they can be represented on the graph with the same type of building block, however, their internal structure (the values of attributes and parameters) can still be different. An example of this would be the various types of NPPs: LWR, PWR, RBMK, HFGR, etc. These categories could even be further divided (e.g. LWR: VVER-440, VVER-1000, AP-1000, etc.) and within such subgroups even the attribute and parameter values would be identical. These standardized building blocks can then simply be used to build the facility level fuel cycle graph of the State.

Since inputs and outputs are standardized, the creation of all possible connections and analysis of the resulting facility level proliferation graph can be done by appropriate software applications.

4. Creating, maintaining and analysing State models

4.1. Creation and maintenance

The model approaches described above are modular in nature, therefore by integrating the building blocks of the generic proliferation model in either model representation into the system, development of a state specific (and facility specific) proliferation models can be realised by virtual drag-and-drop methodology with using state/facility specific parameters and evaluations.

Using this modular approach would have several (crucial) benefits:

- allows a large number of items items on the graph;
- easy creation of complex graphs using simple drag-and-drop method;
- connections of nodes can be easily automated (software)
- provides for utilization of large number of existing graph analysis algorithms;
- provides for utilization of many existing graph visualization software tools;
- requires little effort to maintain the database (connectivity matrix, adjacency list): only few attributes and parameters need to be adjusted or maintained, most of them can be used with their default values.

4.2. Attributes, Parameters and Agency Safeguards Features

Whether the proposed models can be successfully used for IAEA safeguards purposes or not, depends largely on whether suitable attributes, parameters and weight functions could be defined to support the evaluation of safeguards relevant features of a State's nuclear fuel cycle. Several suggestions were already given in the previous discussions. In this final chapter we discuss a few possible options.

4.2.1. Conversion time

In Agency safeguards the "conversion time" of a given nuclear material type is defined as the time required for the production of a significant quantity of weapons grade material from the given material with the assumption that all necessary technology and facilities already exist. If the weights of the edges of the nuclear fuel cycle graph are assigned the processing time required for 1 effective kilogram of material, then the result of a shortest path analysis run for all nodes as starting points will be analogue to the "conversion time" for all nodes, i.e. all material types and fuel cycle stages. The analysis can be easily performed with or without considering undeclared facilities. Generic conversion times can be derived from the generic proliferation model, but the analysis of the State's facility level model will result in State specific conversion times.

4.2.2. Safeguards measures

Safeguards measures such as material verification or containment can be easily incorporated in the models, through the introduction of a parameter proportional to the detection probability of the applied measure and an attribute (yes/no) indicating whether the safeguard measure is applied or not. For example in the material flow model, valves might be added to represent the blocking of diversion routes, or partial cross sections may simulate detection probabilities. Then the models can be easily analysed with or without "applying" various safeguards measures at various pipes.

4.2.3. Effectiveness

The effectiveness of a safeguards measure applied to a selected point in the fuel cycle can be defined as the increase of the distance of the selected point from the destination (nuclear weapon). The effectiveness is maximal if the measure totally disconnects the source node from the destination.

5. Summary

The IAEA has recently requested Member State support in the development of acquisition path analysis methodology and applicable software tools. To support this effort, the initial analysis of the applicability of the directed graph methodology and corresponding network modelling software solutions were carried out. In this paper we described the two possible representations of the nuclear fuel cycle as a directed graph: the transportation model and the material flow network model. It was shown that both models are suitable to form a general framework for the acquisition path analysis methodology. They could be described with similar mathematical formulas and solved with similar analytical methods, which can easily be built into existing software environments readily available to build, manage and visualize large network modelling problems.

If the concept outlined in this paper finds wider acceptance in the professional community, the key tasks of developing acquisition path analysis methodology for IAEA safeguards purposes would consist of the following steps:

- the determination (in appropriate detail) of the set of material types and technological processes that describe the current technological possibilities relevant to nuclear weapons acquisition;
- the identification of all possible (relevant) direct routes between materials, processes that current technology permits;
- the identification and evaluation of the attributes and parameters to be used for the nodes and edges of the graph models;
- the definition of the required analytical goals (weight functions) and corresponding mathematical algorithms;
- the selection (and customization, if needed) the most suitable graph modelling and data management software environment.

We are confident that even if the validity in the real world situations of the actual absolute values obtained through any graph analytical methods might be questioned, the proposed approach would definitely provide a sound objective basis for the comparison of different safeguards measures, or comparison of different States.

Acknowledgement

The authors express their thanks to Mr Akos Peto (IAEA) for initiating this topic and for his interest in and valuable contribution to this work.

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A Little Customs Glossary for IAEA Safeguards: Customs Procedures and Concepts that Matter for the Implementation of Modern Safeguards

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Abstract:
The additional protocols to the IAEA comprehensive safeguards agreements include provisions about the reporting by states of their imports and exports of listed equipment and non-nuclear material, also known as the "trigger list", as well as nuclear materials. Beyond declarations and their verification, IAEA Safeguards also looks at other Imports and exports as part of its efforts to build confidence on the absence of undeclared nuclear activities or material. In all cases, information about international transfers of interest to Nuclear Safeguards is closely related to export control activities. But, if much has been written about the material and equipment to be declared, neither IAEA Safeguards nor Export control related documents provide much explanation about what exports and imports actually are. In fact, precise legal definitions are to be found generally in national customs regulations and international agreements on customs and trade. Unfortunately, these are not necessarily in line with Safeguards understanding. It is therefore essential that IAEA safeguards comprehends the customs concepts and procedures that are behind Safeguards relevant information.

Keywords: IAEA, Safeguards, export control, additional protocol, customs, export, import, legal

1. Introduction

The relations between export control and IAEA Safeguards have been largely explored by researchers in its technical, historical, policy and international law dimensions. This paper will rather focus on the importance of customs legal definitions and processes for the implementation of Safeguards.

The words "import" and "export" appear in both comprehensive safeguards agreements (CSAs)[1] and the model additional protocols (AP)[2]. States signatory to these agreements must declare to the IAEA the import and export of certain nuclear material and non-nuclear material and equipment.

In non-proliferation and export control legal documents and related academic material, these terms are either briefly defined as the transfers of items between States[3], or not defined, assuming that these notions are straight forward and do not require extensive explanatory notes[4]. Import and export refer essentially to customs operations. In the customs context, these terms have precise legal definitions which are both complex and not necessarily consistent with the Safeguards understanding.

More generally, customs procedures and concepts are not well apprehended outside the customs and international logistics community, whereas some of them are key to understand information used by Safeguards in its evaluation of States' declared and undeclared nuclear activities.

This paper will first describe why customs and export control procedures matter for Safeguards and why their misinterpretation can be a problem. It will then describe in the form of a practical glossary, a number of customs concepts and procedures that are little known to the Safeguards community but nevertheless important to understand for the analysis of declared information, of indicators of undeclared activities, and the understanding of trade aspects of nuclear proliferation.

2. Safeguards, export control and customs.

2.1. Forewords on export control

Definitions of export control vary. For the non-proliferation community they essentially refer to controls of strategic trade[5] including WMD related dual use items, weapons and other military related goods and embargoes. At the national level, they include, amongst other things, a licensing component and a border enforcement component.[6]

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1 *INFCIRC/153, art 14, 34, 91, 94, 107*
2 *INFCIRC/540, art 2.a vi and 2.a.ix*
3 See IAEA *Safeguards glossary and chapter 4.2 below*
4 Art 91 of INFCIRC/153 only addresses the question of point of transfer of responsibility between two States involved in an international transaction: *"The Agreement should provide that the States concerned shall make suitable arrangements to determine the point at which the transfer of responsibility will take place."*
5 "Strategic trade" belonged to the cold war voccabulary, but strategic trade controls could objectively describe today's border controls on shipments that can eventually constitute global or national security threats. One should consider the ambiguity of the term "dual use" (see paragraph 5.1. below) and the scope of modern "export controls" exposed in the following paragraph.
6 See Viski A, *The National Implementation of Nuclear Export Controls: Developing a Best Practices Model*, ESARDA Bulletin n°46, December 2011

We propose to look at it in view of two essential aspects:

1. It is an activity enabling state authorities to be informed of relevant trade operations
2. It is a legal and operational tool to act on it.

The first aspect is essential for Safeguards: without the export control licensing process and enforcement activities, State authorities would not be in a position to know of imports and exports to be declared to the IAEA. Conversely, the absence of controls on the import of the same items explains the difficulties that States might have to declare the import of trigger lists items to the IAEA, as required by the 1993 Voluntary Reporting Scheme, or even confirm an import on IAEA request (AP art 2.a.ix b)).

It is important to outline that modern export controls cover much more than exports: they include transit, transshipment, brokering, intangible transfers and financial operations. But exportations remain the bulk of what could be more accurately described as strategic trade controls (STC), and are at the heart of AP declarations to the IAEA.

We will therefore essentially focus on export procedures and use the term "export control" which is still widely used in the licensing, enforcement and academic communities.

2.2. Why do export control and customs matter to safeguards?

Three main reasons can be listed here:

- States AP declarations of export of non-nuclear material and equipment (INFCIRC/540, 2.a.ix) originate from export control systems: in most cases they are listings of delivered export licenses[7]. These export control systems use customs laws and definitions as a legal basis.
- The understanding of national export control systems including their licensing enforcement components, are part of the State factors analysis conducted by IAEA Safeguards[8].
- Much of the trade information used by IAEA Safeguards as indicators of undeclared activities, incomplete or wrong reporting by States is directly or indirectly generated by export control activities including enforcement[9]. Additionally, analysis of trade data deriving from customs declarations have started to be used to further safeguards verification.[10]

For these reasons, it is essential that IAEA Safeguards understands the origin and nature of the trade information it has to deal with.

2.3. Why is it a challenge?

Despite the fact that "export" and "import" are used throughout IAEA Safeguards key documents, no legal definition of these terms is readily and publically available in Safeguards agreements, the NPT, or the Zangger committee publications.[11] The common sense interpretation is that export and import refer to the movement of commodities[12] between Countries, defined by their political boundaries. The definition given in the IAEA Safeguards glossary confirms this interpretation[13].

One would think that more precise definitions would be found in export control regulations and documentation. This is generally not the case. As it is well noted by some authors,[14] public international export control guidelines including Nuclear Suppliers Groups' (NSG) documents, and much of the literature around export control do not expand on the definition of these terms. There is also little answer to be found in national export control regulations.

In fact, precise legal definitions of export and import, on which national export control regulations are based[15], are to be found essentially in general customs codes and laws[16]. Because of their important legal and fiscal implications for daily international trade, terms relating to customs operations are necessarily defined with precision, and their interpretation is further refined by abundant case laws.

Observing these definitions in national regulations or in international trade agreements, one can realize that these definitions, legal processes, and underlying concepts can be complex. They are also not always consistent with the way IAEA Safeguards understands them. In order to properly understand Safeguard export declarations, export control systems and trade indicators, IAEA Safeguards and their national counterparts, the SSAC[17], must understand the various existing legal definitions and their implications for safeguards.

Definitions may vary from one country to another, but some common standards can be observed .[18] The 2006 Revised

7 They are more rarely records of actual exports.

8 See Everton C,. Leslie R,. Bayer S,. East M, *Transparency and other State-Specific Factors: Exploration of ideas for evolving IAEA's System of State-Evaluations and Safeguards Implementation*, *ESARDA Bulletin* n°46, December 2011

9 Typically, public indictments and related press articles, journalists investigative work or information voluntarily provided by States to the IAEA.

10 See VERSINO C.,. CHATELUS R,. COJAZZI G,. CONTINI F,. TARVAINEN M,. TSOIS A, *Global Trade Data to Support IAEA Safeguards*, *ESARDA Bulletin*, n°45, June 2010.

11 The Zangger committee is the only export control group mentioned by the NPT Review Conference.

12 This paper will not address the control of intangible transfers which are not included in Safeguards declarations and only marginally involving customs.

13 See paragraph 4.2.below on import and export definitions

14 See Viski A, *The National Implementation of Nuclear Export Controls: Developing a Best Practices Model*, *ESARDA Bulletin* n°46, December 2011

15 Under the term « national export control », we also include customs union export control like EU export controls.

16 For example, the European export control regulation refers explicitly to the European community customs code, for example to define "export" and "re-export".(Regulation 428/2009, art.2)

17 State System of Accounting for and Control of nuclear material

18 This paper will largely leave aside US export procedures and export control regulations, which are original in many respects, in order to focus on the most common cases.

Kyoto Convention on the Simplification and Harmonization of Customs Procedures (Kyoto convention), World Trade Organization (WTO) documents (Especially definitions deriving from the Uruguay Round of the General Agreement on Tariffs and Trade - GATT) and the World Customs Organization (WCO) Glossary of International Customs Terms are good reference points to understand common practices in international trade and customs procedures.

3. The Framework of Customs activity

3.1. Customs territory

According to the Kyoto convention, "*Customs territory means the territory in which the Customs law of a Contracting Party applies.*" "Customs territory" is key to understanding many other customs concepts: import, export and all related procedures refer to the borders of the customs territory. The customs territory does not necessarily match other dimensions of the national territory, like the political territory or the tax territory: territories within political boundaries of a State might be outside the customs territory (e.g. free trade zones) [19] or be separate customs territories (e.g. certain overseas territories). Conversely, several countries defined as politically independent States can be part of the same customs territory (case of a customs union). We will further explore the implications of the customs territory definition in the paragraphs below.

3.2. Free trade zones

There is no official international definition of a free trade zone (FTZ). The Kyoto convention definition is limited to tax aspects, which is too restrictive to describe the reality of modern FTZ. Many definitions can be found in web documents. Each FTZ is different and every country has different FTZ regulations or even different names for them.[20] The following definition was found on web sites relating to Turkish FTZ:

"Free Zones are defined as special sites within the country but deemed to be outside of the customs territory and they are the regions where the valid regulations related to foreign trade and other financial and economic areas are not applicable, are partly applicable or new regulations are tested in." [21] FTZ are established for economic development purposes, to attract foreign investments, trade and employment.[22] FTZ should not be confused with *free trade areas* and *free trade agreements* (see paragraph 3.3. below).

To be more precise, FTZ have in general the following common features:

- An area outside the customs territory ("deemed outside the country[23])
- Specific trade or manufacturing activities: FTZ are "specialized" in certain products, certain activities and/or trade with a defined partner country.
- No import-export procedure with the rest of the world (only with the mainland customs territory)
- Total or partial exemption from business related laws applicable to the rest of the country (e.g. social/labor laws, corporate law and/or import-export restrictions)
- Exemption from national taxes and import-export duties
- Limited state enforcement and control activities (or at least a special framework to it).

A few observations can be made that are relevant for Safeguards:

- FTZ are outside the customs territory, i.e. from a legal customs perspective export and import take place between the mainland customs territory and the FTZ, but not between the FTZ and the rest of the world.
- If export control regulations or case laws do not specifically address FTZ, the customs definition should apply by default: movements of goods out of the FTZ are out of the scope of export control and might not be reported by the State.[24]
- FTZ are established to limit governmental oversight and administrative burden on businesses. This may limit the government legal, but also practical ability to exert the oversight necessary to the collection and reporting of Safeguards relevant activities and exports. In some cases customs is not allowed to enter the FTZ, which is managed and controlled by specific governmental, if not private organizations (see The Kyoto convention on Customs controls in FTZ below)

Procedures specific to FTZ such as authorizations procedures to establish trade or manufacturing activities in FTZ are not a substitute for export control permits and licenses, neither in legal terms nor in practice. Similarly, some countries have procedures to ensure that export licensed items exported to a FTZ will be monitored, if the exporting State requires so. Such arrangement should not account for an export control process. They rather reflect an attempt by FTZ regulators to overcome licensing authorities' reluctance to deliver export license for an FTZ destination.

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[19] Typically, Singapore IRAS e-Tax Guide published by the Inland revenue authority of Singapore states that *Strictly speaking, goods are treated as "imported" once they are brought into customs territory. "Custom territory" means Singapore and the territorial waters thereof but excluding any Free Trade Zone.*

[20] FTZ are sometimes called a free economic zone, duty free zone, tax free zone, trade free zone, export processing zones, special economic zones, etc….

[21] *http://www.turkishtradechicago.org/freeTradeZones.html*

[22] For further details on FTZ around the world and their definitions , see *Special Economic Zones performance, lessons learned and implications for zones development*, World Bank, FIAS, APRIL 2008.

[23] A common expression in FTZ regulations.

[24] Some encouraging high court rulings in the UAE and Malaysia on Intellectual Property Rights violations in FTZ show that the concept of FTZ as a territory "deemed outside the country" can be overcome for certain laws. (See Cooper D, *Securing the Supply Chain, the Role and Responsibility of Free Trade Zones*, WCO "*Connectivity*" bulletin, n°67, February 2012);

The Kyoto convention on Customs controls in FTZ

The Kyoto convention recommended practice on FTZ states, amongst other things that:

"The Customs shall have the right to carry out checks at any time on the goods stored in a free zone.

[…]

But also that:

- *Admission to a free zone of goods brought from abroad should not be refused solely on the grounds that the goods are liable to prohibitions or restrictions other than those imposed on grounds of :*
- *public morality or order, public security, public hygiene or health, or for veterinary or phytosanitary considerations; or*
- *the protection of patents, trademarks and copyrights, irrespective of country of origin, country from which arrived or country of destination*. (export control is not listed, unless arguably understood as public security)

[…]

- *The only declaration required for goods on removal from a free zone shall be the Goods declaration normally required for the Customs procedure to which those goods are assigned.*[…]" (i.e. import into mainland or foreign customs territory)
- "- *Where a document must be produced to the Customs in respect of goods which on removal from a free zone are sent directly abroad, the Customs should not require more information than already available on the documents accompanying the goods.[…]"*

The World Bank estimated that in April 2007, there were *approximately 3,000 zones in 135 countries, accounting for over 68 million direct jobs and over $500 billion of direct trade-related value added within zones.*[25] These figures are likely to have swollen since then, increasing the chance that trade or manufacturing activities relevant for Safeguards and export controls take place in such zones.

3.3. Free trade agreements and free trade areas

Free trade areas (FTA) and free trade agreements are not related to the concept of free trade zones, although the terms are occasionally confused.

Art. XXIV of the General Agreement on Trade and Tariffs (GATT) defines FTA as " *[…] a group of two or more customs territories in which the duties and other restrictive regulations of commerce […] are eliminated on substantially all the trade between the constituent territories in products originating in such territories."* FTAs may be established between countries that don't have common borders[26].

The WCO glossary of customs terms defines a free trade area as an *"entity formed by the Customs territories of an association of States and having in its ultimate state the following characteristics:*

- *the elimination of Customs duties in respect of products originating in any of the countries of the area,*
- *each State retains its Customs tariff and Customs law,*
- *each State of the area remains autonomous in matters of Customs and economic policy,*
- *trade is based on the application of rules of origin, to take account of the different Customs tariffs and prevent deflection of trade,* (see paragraph 4.3. below on "country of origin")
- *the elimination of restrictive regulations of commerce within the free trade area.*(e.g. quotas, import-export procedural costs, export subsidies)

For Safeguards purposes, it is important to note that:

- Free trade agreements are essentially about lowering the cost of bilateral movements of goods, and generally don't affect export control obligations.
- Customs territories of parties to the agreement remain untouched: Import and export procedures are still in place and can serve as basis for export control, regardless of trade facilitations established by the agreement.

3.4. Customs unions

The GATT defines a customs union as follows: *"A customs union shall be understood to mean the substitution of a single customs territory for two or more customs territories, so that*

(i) duties and other restrictive regulations of commerce […] are eliminated […] and,

(ii) […] substantially the same duties and other regulations of commerce are applied by each of the members of

[25] *Special Economic Zones performance, lessons learned and implications for zones development, World Bank, FIAS, APRIL 2008.*

[26] E.g. FTA between the US and Chile or Canada and Israel

the union to the trade of territories not included in the union."

In other words, in its ultimate form[27], a customs union is characterized by no internal border control on goods and a common external trade policy, including export control.

In the case of the European Union, and contrary to free trade agreements, there is no export or import procedure among Member States, although statistical and fiscal declarations, and certain special trade authorizations[28] still apply to exchanges of goods between States parties to the union. The export control regulation is set at the EU level.

Customs unions exist in different parts of the world[29]. They generally apply to the movement of goods. They should not be confused with agreements on visas and the movement of persons such as the establishment of the Schengen area between certain European States, which are irrelevant to Safeguards and export control.

For Safeguards purposes, it is important to retain that:

- Special legal provisions must be in place to ensure that information on transfers of relevant commodities between States of the Customs Union is collected and reported despite the fact that there is no "export" procedure involved per say.
- States must be capable in practice, to collect such information in the absence of customs procedure.
- For non-proliferation purposes, common export control regulation and policies for exports to outside the union must be in place to compensate for the free movement of goods within the union.[30]

4. Customs procedures

4.1. Export control enforcement

Customs "controls" are simply defined by the Kyoto convention as *"Measures applied by the Customs to ensure compliance with Customs law"*. The WCO customs glossary does not define "export control". But for customs as for the non-proliferation community, "export control" refers to controls on shipments of items and technology that may contribute to proliferation and constitute a threat to global and national security.

For export control, customs work consists in verifying the validity and applicability of licenses presented together with the customs declaration as well as detecting and intercepting shipments moving through the border, without a license, in violation of export control laws. Activities can include the range of customs techniques and processes including profiling of high risk shipments, intelligence, documentary and physical controls and post-shipment investigations.

It is important to understand that in practice, if customs controls are essential to export controls, export control (not mentioning Safeguards reporting) is marginal in customs activity. Revenue collection, commercial controls and other interdictions usually rank much higher in customs priority list. In most countries, the techniques described above are hardly applied to export controls, or only by a small specialized group outside the mainstream of customs activities. In this field, customs often rely upon information from other services of the export control apparatus.

Security related controls essentially take the form of detection of dangerous materials by technical means (e.g. radioactive material), which are more about preventing terrorist acts than preventing the spread of WMD related goods and technology.

The general reluctance of customs to grasp the "dual use" export control subject is due to cultural, legal, practical, organizational and technical reasons that too complex to be described in this paper, but it can be illustrated by the fact that the WCO Glossary of (155) International Customs Terms does not include any definition directly related to export control (like "dual use", "export control", "end use", "strategic").

This does not mean that customs procedures are not important for export control and reporting to the IAEA, as we will see.

4.2. Import and export

The Kyoto convention provides the following definitions: **Import** *is the act of bringing or causing any goods to be brought into a Customs territory;*

Export *is the act of taking out or causing to be taken out any goods from the Customs territory.*

From a customs perspective, export and import procedures are closely related to the notion of customs territory, as defined above. They also relate to a range of procedures and customs status beyond outright export or import: re-exports, transit, temporary exports, outward-inward processing, etc.., which have legal implications in terms of duty and taxes, trade restriction and related controls. Some of these terms are defined below.

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27 Not all customs unions have reached the stage of integration described here. For example, the EU-Turkey customs union agreement does not (yet) merge the two customs territories. At this stage it should rather be described as a free trade agreement.

28 E.g. for transfers of 428/2009 Annex IV items, including trigger list items

29 Examples include: Andean Community (CAN) 1988, East African Community (EAC) 2005, Customs Union of Belarus, Kazakhstan and Russia 2010, EU — Andorra 1991, EU — San Marino 2002, EU — Turkey 1996, Israel — Palestinian Authority 1994, Southern Common Market (MERCOSUR) 1991, Southern African Customs Union (SACU) 1910, Switzerland — Liechtenstein 1924 .

30 All these elements are present in the European export control regulation, at least on paper.

It should be noted that for the same international trade operation, export procedures in exporting States and import procedures in importing States are generally not connected. Countries cannot readily identify an import based on a customs export declaration in the country of exportation[31].

From a Safeguards perspective, there is little doubt that export and import are meant to be about movement of goods across the State's political boundaries rather than its customs boundaries: the Safeguards glossary published by the IAEA defines **export** and **import** as "*The international transfer of nuclear material subject to IAEA safeguards into and out of a State.".* Art. 91 of the CSA seems to place the notion of "transfer of responsibility" at the heart of the export-import reporting process. This concept is laid down in the framework of nuclear material transfers, but is not necessarily well adapted to international trade of industrial items like those of the Annex II of the Additional Protocol[32].

The differences between IAEA definitions and customs definitions of import/export must be well understood by IAEA Safeguards, in particular the fact that:

- Export declarations sent to the IAEA may have to include movements of goods beyond exports as defined by customs, and possibly export control regulations
- Regulations set-up to fulfill international trade declaration to the IAEA must specifically and explicitly address this gap between customs and political boundaries.

4.3. Country of origin

According to the Kyoto convention, the *"country of origin of goods means the country in which the goods have been produced or manufactured, according to the criteria laid down for the purposes of application of the Customs tariff, of quantitative restrictions or of any other measure related to trade."*

The definition of the country of origin of a good is essential to determine customs import procedures, level of duties and applicable regulations. It follows complex rules that can include, for example, considerations about the percentage of value added to the imported commodity in each country along the international supply chain.

It is important to understand that the origin of a good as it appears in customs procedures, documents and statistics, is not related to the "made in" marked on consumer goods or the "origin" of material and equipment understood in the safeguards context.[33]

4.4. Country of destination

The country of destination of an export is part of the standard information required in export procedures, but its importance is very secondary compared to the importance of the country of origin in an import procedure. In fact, except for export control, for which it is an essential authorization criteria, and trade statistics, the country of destination rarely matters for customs, hence the relatively limited legal provisions and enforcement efforts around this information. The Kyoto convention, with a trade facilitation view, even recommends that for outright exports (i.e. not temporary), *"the Customs shall not require evidence of the arrival of the goods abroad as a matter of course."*

This comes in sharp contrast with export control procedures and safeguards export declarations which are very much focused on the country of destination and end-use. The destination of an export described in customs information (international trade databases for example) is not necessarily corresponding to the end-use location of interest to Safeguards.

4.5. Transit

According to the revised Kyoto convention, *"customs transit means the Customs procedure under which goods are transported under Customs control from one Customs office to another."* In other words, customs transit is a procedure by which goods can travel through a customs territory from one border point to another, without being cleared through customs as an import (and consequently as an export).

Transit is sometimes meant less restrictively, but in the legal context of an import-export operation, the customs definition should prevail. The T.I.R.[34] procedure for land transportation is the most well-known transit procedure, but every customs law system includes provisions on customs transit. A typical example is the movement of uranium concentrate from Niger in "transit" through Benin or Côte d'Ivoire to be exported from ports on the Gulf of Guinea.

Transit procedures usually include mechanisms to guarantee that the commodities will get out of the country as they came in: administrative procedures, seals, GPS tracking system, security deposits for the amount of duties and taxes involved, time limits for transportation, customs escort of convoys and/or information exchange systems

[31] Recent concepts of secured supply chains, briefly discussed at the end of this paper, partly address this problem by linking export and import procedures for a given trade operation.

[32] For example, the so-called AQK Network exported enrichment equipment to its Dubai logistics base, storing it without necessarily an assigned client. What is the relevance of the "transfer of responsibility" in a scenario like this? In the framework of additional protocols, what should be declared by States involved?

[33] For example in Art.6.b of the Model AP.

[34] "Transit International Routier", defined by the 1975 Customs Convention on the International Transport of Goods under Cover of TIR Carnets. Trucks circulating under this status carry the sign T.I.R.

between customs offices at the point of entry and at the point of exit.

Current international export control guidelines and many national regulations require licenses for transit as they do for exports. In practice however, customs ability to control goods in transit may be very limited, regardless of the obligations set forth by export control regulations. Political implications[35] if not general customs law may render the enforcement of such provisions by customs ineffective on the ground.

Form a Safeguards perspective, transit should have no impact in terms of declaration obligations and their verification[36]. But understanding transit can help interpret safeguards relevant information originating from export control and customs activities.

4.6. Transshipment

Transshipment and transits are sometimes confused in export control literature and even legal documents. According to the Kyoto convention, *"transshipment" means the Customs procedure under which goods are transferred under Customs control from the importing means of transport to the exporting means of transport within the area of one Customs office which is the office of both importation and exportation.* Transshipment occurs for example in free trade zones but also in areas under customs like customs warehouses or international areas in ports. One of the big differences is that keeping the transfer within one controlled area, means that heavy duty and tax security procedures mentioned above for transit, are less needed.

In terms of control and enforcement on the ground, limitations are as significant as for transit, although they may be more driven by economic and practical enforcement parameters than political considerations.

Unlike transit, transshipment is not explicitly mentioned in Safeguards agreements, but it is reasonable to assume that transshipment is also "transparent" with regards Safeguards reporting of international transfers.

4.7. Outward / inward processing

In this processes, goods are temporarily imported (inward processing) or exported (outward processing), to be processed and transformed. For inward processing, the purpose is to avoid the payment of import duties on components of commodities intended for export. For outward processing, the purpose is to calculate the import duties on the basis of the value added by the manufacturing process abroad rather that the whole value of reimported goods.[37]

It is unclear whether such facilitation procedure was used for proliferation purposes, but certain international manufacturing operations conducted by proliferation networks would have been perfect candidates for it. It is not impossible that proliferation networks use such procedures to save money or, on the contrary, don't use them when they should, to avoid exposure[38].

5. Few other ambiguous terms

Safeguards Staff should always try to understand in which sense these terms are used, in each context.

5.1. Dual use

In the non-proliferation community, the term "dual use" is known to be ambiguous, as it refers to two contradictory definitions: the Wassenaar Arrangement definition focusing on military v/s non-military uses[39] and the NSG definition focusing on nuclear v/s non-nuclear use.

But the ambiguity goes beyond these two definitions when a customs and/or Safeguards analyst perspective is taken:

- Dual-use is sometimes used by analysts and expert as a way to describe the strength of an indicator[40] of undeclared nuclear activity, regardless of the fact that it is on control lists or not. In this sense, the shipment of a dual use item indicates an activity with a certain level of probability.
- Dual-use is also found sometimes to describe export controlled items regardless of whether they are dual use (in the NSG or Wassenaar sense), especially designed and prepared, or controlled for other reasons. This misuse of the term "dual use" may be in relation to the fact that the European export control regulation is known as the "dual use regulation."[41], although it covers more than WMD related dual use goods and includes especially designed and prepared items (i.e. not dual use).
- Finally, the expression "dual-use chemicals" is used in the context of the WCO Global Shield programme to

[35] For example, landlocked countries may consider as illegitimate, controls conducted by transit countries on shipment destined to them. The same observation can be made on major international transit routes like intercostal canals used by international shipping routes.

[36] As clearly stated for nuclear material transfers in Art 91 of the CSA

[37] To take an example, UF6 processing equipment might be exported to be coated abroad. With outward processing, the import duties on the re-imported final product would be a percentage of the coating cost rather than a percentage of the whole equipment value.

[38] Both patterns have been seen in procurements by proliferation networks: trying to gain more money by adding customs/duty fraud to export control violations and accepting to lose money, like tax refund, to avoid controls (and be detected because of this abnormal pattern).

[39] This definition seems to be also to be the one used in non-proliferation agreements on biological and chemical weapons as well as delivery systems.

[40] Indicator strength is a concept developed in IAEA safeguards internal documents like the "Physical Model"

[41] *COUNCIL REGULATION (EC) No 428/2009 of 5 May 2009 setting up a Community regime for the control of exports, transfer, brokering and transit of dual-use items.* This regulation sets up a Community regime for the control of exports, transfer, brokering and transit of dual-use items, especially designed and prepared item and related technology from the various international non-proliferation and arms control regimes in a single regulation.

describe listed explosives precursors. Technically, other products, like drug precursors, can be seen as dual use in a customs context, with procedures very similar to the ones in place for WMD related dual-use items.

5.2. Precursors

"Precursors" have also different meanings in different contexts:

- For the export control community, precursors refer unambiguously to WMD precursors, like compounds used to manufacture combat gazes.
- For most of the customs community, precursors refer to drug precursors: chemicals used to manufacture natural or synthetic drugs.
- In the Global Shield context, precursors refer to explosives precursors: chemical products that can be used to manufacture improvised explosive devices.

Interestingly all three definitions are embedded in similar licensing and export control procedures, but people involved in each of these contexts are not necessarily aware of the two other meanings of the term.

5.3. Re-export

"Re-export" has different meanings in different customs regulations as illustrated in the three examples below:

- The UN Statistical office, which compiles and publishes international trade records based on national customs information, defines Re-export as: "*Exports of foreign goods in the same state as previously imported.*"
- The WCO glossary defines re-export as: *"Exportation from a Customs territory of goods previously imported into that territory*", i.e. not necessarily moving back to the territory it was originally imported from. That definition is close to the US export control definition of a re-export and to the NSG definition of re-transfer.
- The European Customs code defines re-export as *"Customs treatment of non-Community goods that are taken out of the customs territory (Art. 182 CC)."* Re-export does not apply to goods that have gone through the full import procedure, but only those under temporary or suspending procedures like transit, customs warehouse or inward processing.[42]

Other definitions might exist, requiring in each case specific clarification efforts on the part of users and readers of this term.

5.4. International trade licenses

An international trade license is defined in the WCO glossary on international customs terms as an *"authorization issued by a competent authority for the importation or exportation of goods subject to restriction."* It is the only term amongst the 155 listed in the glossary, which one might think relates to export control. But even then, an export or import license is not necessarily related to trade controls on WMD related goods or weapons. Import and export licenses exist for technology, artworks, archeological objects, plants and animals, medicines, chemicals or textiles.

6. Few recent concepts

New concepts and international standards for customs procedures and operations have arisen in the recent year, with a view to securing the international chains of supply from terrorist and other criminal activities while facilitating legitimate trade.

The most significant initiative is the WCO SAFE Framework of Standards[43], setting standards for the collaboration between the private sector and different border services involved throughout the supply chain, rather than letting customs of each State controlling imports and exports in isolation. The guidelines also set standard for the auditing and licensing of Authorized Economic Operators (AEO)[44] which can benefit from lighter control procedures on both ends of the supply chain. The SAFE standards have started to be implemented in a number of countries, beginning with the most developed economies.

The SAFE recommendation are not specifically geared towards export control, but bear concepts and procedures that should hopefully have positive consequences on export controls, and consequently on the quality and completeness of information provided to the IAEA. However, exploring these implications would go beyond the scope of this paper.

7. Conclusion

As we have seen, a number of customs concepts are not necessarily simple, straight forward and consistent with the vocabulary used by the IAEA Safeguards community and even the non-proliferation community at large. In this field like in other contexts, these terms and procedures are not well understood beyond the little community of customs and international logistics, the same way IAEA terminology is not well known outside the nuclear Safeguards community.

They can however have implications for Safeguards, in terms of legal interpretation, and information analysis. To avoid

[42] The EU export control regulation specifies that it applies to both exports and re-exports, as defined by the European Customs Code.

[43] http://www.wcoomd.org/files/1.%20Public%20files/PDFandDocuments/SAFE%20Framework_EN_2007_for_publication.pdf

[44] Defined in the SAFE framework of standard as: *"a party involved in the international movement of goods in whatever function that has been approved by or on behalf of a national Customs administration as complying with WCO or equivalent supply chain security standards. Authorized Economic Operators include inter alia manufacturers, importers, exporters, brokers, carriers, consolidators, intermediaries, ports, airports, terminal operators, integrated operators, warehouses, distributors".*

misunderstandings, it is important that Safeguard analysts, legal experts, inspectors, but also national SSAC be aware of the various meanings of these terms, recognize which specific definition applies in each case and which procedures have generated safeguards relevant information.

It is also essential that everything be done to facilitate the mutual understanding and information sharing between national SSAC, licensing authorities and customs in each State with AP in force. Bilateral meetings with the IAEA on the implementation of AP provisions as well as export control trainings can be opportunities to bring them around the same table. The communication between these three worlds doesn't come naturally and is nevertheless a prerequisite to complete and correct reporting of trade activity to Safeguards, as well as efficient export controls.

Systematic classification of civil society contributions to nuclear safeguards

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Abstract:

Civil Society is increasingly involved in the policy area of international arms control. Their opportunities are very limited for compliance control in the nuclear nonproliferation regime due to its particular sensitivity. The severe gaps of nuclear safeguards with respect to the capabilities to detect clandestine facilities render marginal civil society contributions highly influential and controversial. More and more data get available for the civil society that can be used to expose potential violations of the NPT. A systematic framework is presented to classify civil society contributions that allows for a systematic study. This classification uses the two parameters (a) affected safeguards stage and (b) degree of integration with the official procedures. These parameters may have the following defined values:

(a) The affected safeguards stage can be

- *i. Development and demonstration of new methodologies and technologies*
- *ii. Fact finding and data gathering*
- *iii. Sharing and publication of data and information*
- *iv. Technical analysis of data and information*
- *v. Determination of non-compliance*
- *vi. Political interpretation*

(b) The degree of integration can be

- *i. Without a relation*
- *ii. Indirect connection*
- *iii. Informal interaction*
- *iv. Official contribution or mandate*

A prominent example for civil society contributions is the increasing availability and capability to acquire and analyze satellite images. An emerging field is environmental sampling, analysis and related atmospheric transport simulation. These and other opportunities are put in the systematic framework to discuss their demonstrated and potential impact. In particular, possible contributions that civil society may offer for improving the detectability of unreported facilities and activities are considered with their chances and risks.

Keywords: civil society; verification; nuclear arms control; Nonproliferation Treaty

1. Introduction

Civil society plays an increasing and influential role in many fields of global governance. This is clearly manifested, e.g. in human rights issues, development policy and environmental protection treaties. The international arms control and particularly the verification of treaty compliance are considered as sensitive policy areas for national and international security such that to assign a responsible role to non-state actors is less likely. In principle, self-determined action within the context of the so- called *Whistleblowing* or *Societal Verification* (Rotblat 1993 [1], Deiseroth 2000 [2] and 2008 [3]) is always possible, however, an official agreed-upon role in the official treaty verification is difficult to achieve. Therefore, the contribution of civil society is sometimes called *Unofficial Monitoring* (Bruneau, 2006 [4]). This, however, does not include all other possible cases. Exceptions are found in the conventional arms control. One example is the landmine monitoring operations of the International Coalition to Ban Landmines (ICBL) serving as the main tool to gather information for the Ottawa Anti-Personnel Landmines Convention.

This article focuses on a systematic classification for the various kinds of contribution of the civil society to treaty verification in the nuclear non-proliferation regime. One special motivation for this is deduced from the partial technical failure paired with partial political constraints and interest-driven interpretations of the official system. The glaring gap of the inspection efforts for the Non-Proliferation Treaty (NPT) is the lack of technical and legal instruments to detect clandestine facilities with illegal activities. This remains virulent due to the non-ratification of the additional protocol. Hopes lie in increasing data that are also made available to help expose possible treaty violations. Satellite pictures by Yongbyon, Natanz and Al Kibar are common examples. New efforts are being made to close the identified loopholes of the official verification with new technologies. Based on a systematic classification, this paper analyses systematically which contribution the civil society can offer on different levels of verification and with varying degrees of integration to the official procedure.

2. Objectives and competences of verification

The United Nations[1] officially defines verification of international treaties, as follows:

> *"Verification involves the collection, collation and analysis of information in order to make a judgement as to whether a party is complying with its obligations."*

The verification of a treaty ensures compliance and strengthens the international security. The objectives of verification can be differentiated and are multifaceted:

- Assurance of compliance
- Detection of non-compliance to obligations and security
- Deterrence of treaty violations
- Confidence-building through transparency and openness

Verification is considered as an essential element of all arms control treaties and disarmament agreements. The competence is well defined:[2]

> *"Verification [...] is conducted by the parties [...] or by an organisation at the request and with the explicit consent of the parties [...]."*

According to this, only state parties as well as their respective assigned agencies may conduct verification. In the case of nuclear non-proliferation, these are international organisations supported by the states.

This paper investigates the contributions of civil society to the verification of nuclear arms control treaties. The article follows the comprehension of civil society proposed in the work of Gunnar Jeremias (2011 [7]). This is based on the definition of civil society as the "third sector" in distinction from the state and market sectors.[3] Civil society organisations and individuals which are active in verification and monitoring generally act independently and regardless of state directives or profit interests. It includes non-governmental organisations, media representatives, technical experts as well as persons who have access to information about illegal activities.

In view of the much-needed expertise, many of these organisations and individuals become almost mandatory members of the academia, and can be described as *epistemic community* according to Haas (1992 [9]). This concept by Jeremias (2011 [7]) also implies, in accordance with the methodology of peace research, the existence of implicit normative commitment of scientists. In this sense, civil society organisations and individual actors fulfil the function of establishing public transparency in compliance issues.

Representatives of civil society cannot take verification functions directly. However, their expertise could be considered by states or other competent international organizations under certain conditions.

3. Systematic examination of the contribution of the civil society to verification

Generally, it can be declared that the information acquired and reported by the civil society can be used by states and the IAEA to stimulate, compare or supplement their verification activities. Even more substantial is definitely the added input value of civil society, thereby increasing the transparency of databases and improves the findings of official verification as well as the public dissemination of information about suspected illegal or doubtful activities.

To better estimate the contribution of the civil society to verification, this article suggests a systematic analytical framework to classify concrete activities into different levels of verification and determine how strong they are integrated into the official verification process. These two parameters define a matrix in which each civil society contribution can be classified. The columns cover the level and the rows the degree of integration (see table).

The levels of verification include three stages (fact-finding, review, assessment), which are designated by Dekker (2001 [12]). They are expanded with the level "Determination of non-compliance through legal and normative interpretation" and framed by the preparation-phase and post-processing-phase. The degree of interaction, proposed by Meier/Tenner (2001 [13]) is added to the case that a norm does exist but not a treaty with official verification.

The "political assessment of non-compliance" (which is hereby referred to as post-processing phase) is not included in the area of verification but rather in the area of compliance policy. The dividing line between verification and compliance is patterned after the work of Gunnar Jeremias (2011 [7]). He recognized that the verification debate of the 80s was highly influenced scientifically leading to a positivist perspective on compliance. However, in many cases, this is not compatible with the reality of the treaty or with state compliance policies. Since treaty norms are subject to interpretation, the evaluation of compliance is always a political action, which is seen as subsequent step to the actual verification based on the used definition. With this perception, Jeremias [7] confirms the findings of Chayes and Chayes (1995 [14]) that compliance assessment is always a political process.

Each contribution by the civil society can be classified in the matrix including the capabilities and competencies of different actors. Civil society actors contribute, for

1 UN General Assembly 2007. [5]
2 UN Disarmament Commission 1988 [6].
3 cf Frantz/Martens, 2006: 18. [8]

instance, not only in the disclosure and dissemination of information but also in political assessments. The better they can achieve this task, the more access they have to restricted information. Independent experts with special understanding of data and analytical procedures are also capable to conduct technical analysis and legal examinations. They can also develop and test novel methods. The prerequisite for the success of these contributions is the freedom of expression and legal protection from disseminating information, which is undesirable by the state.

The presented analysis matrix here is only a rough example. A systematic survey of a great number of historic activities by the civil society requires further research. However, with the following list, a preliminary evaluation can be made on the positive effects of civil society activities for treaty verification. Each of these will be illustrated by a practical example.

- Important contributions to the development and demonstration of novel verification methods have been achieved. Thus, the foundations of new verification measures and successful treaty negotiations have been laid. Examples are the development of the ultra-trace analysis with an atom trap for krypton-85 as well as the development and demonstration of seismic detection of nuclear tests.
- The disclosure of problematic activities through whistleblowing facilitates an early warning. Mitchell (2000 [15]) regards the essential contribution of non-traditional sources as fire alarm. The best known example is Mordechai Vanunu and secondly, the Iraqi defector Khidir Hamza.
- Open access technologies enable civil society actors to verify nuclear activities. This happens also at instances where the official verification system fails. Novel sensors provide additional opportunities. Relevant examples are found in the analysis of satellite images for the detection of nuclear facilities. The surface nuclear tests were detected worldwide by many radiation protection laboratories and were reported in many scientific publications.
- Similarly, the civil society can provide additional information to fill up the gaps of verification and make recommendations for political decisions. This is mostly indirectly facilitated through open source information. Satellite images are often provided on the internet, analysed and annotated after a location has been detected via other means, like the alleged Syrian nuclear reactor after the Israeli attack.
- Confidential treaty documents are purposely forwarded to non-state actors who do not hesitate to publish them via internet. The goal of transparency, which is only marginally supported by the official system, can then be achieved through this. The website WikiLeaks is particularly popular in this matter. For years, the confidential reports on the Iranian nuclear program are published immediately after their completion through the IAEA on the website of ISIS (Institute for Science and International Security).
- The civil society also has a function in the processing and presentation of open knowledge base. This is important most of all for countries without own NTMs to lessen knowledge gaps. They help achieve transparency for public information and in emergency cases, compose counterfactual statements against official declarations of single states or verification organisations. The database on seismic events of the U.S. Geological Survey (USGS) is one example. The location, point in time and the seismic magnitude of the second North Korean nuclear test was published by Kalinowski (2009a [17]) via press release and finally transmitted by news agencies in ten different languages.

This list could be supplemented by theoretically possible activities of the civil society. However, this article does not attempt to provide a more speculative view.

However, there is also the risk of negative impacts. Groups of the civil society can be prone to an interest-driven focus of work. Normally, the data used by these groups is not authenticated and thus, quality control is only possible to a certain extent. There is a potential risk of false alarms which are difficult to verify and the risk of false accusations motivated by unilateral interests.[4] These risks have to be counteracted and addressed without restraining the positive effects.

The civil society can strengthen at least partially the verification of nuclear arms control treaties. It can contribute to achieve the different goals of verification (assurance of compliance, detection of non-compliance, deterrence of violation of the treaty and transparency) more completely. The potential of the civil society to contribute to the verification can still be further improved and utilized. Proposals for the improvement of quality and scope of civil society contributions especially for their formal integration into the official process of verification can be found in Crowley/Persbo 2006 [16]. Deiseroth 2008 [3] demands a more effective legal protection for individuals exercising their responsibility. This paper works on the thesis that the role of non-state actors in the verification of nuclear arms control treaties can be strengthened with the support and use of novel scientific and technological developments and methods.

Acknowledgement

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4 Mitchell 2000 [15] discusses the financial costs of the analysis of false alarms and their political costs

monitoring of international treaties of the Carl Friedrich von Weizsäcker - Centre for Science and Peace Research (ZNF) for the inspiring discussions and insight. I thank Julie Ann Daludado for translation of the German manuscript and Paul Kaiser for editorial support.

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<table>
<tr><td>Affected safeguard stage
Degree of integration with official procedures</td><td>Development and demonstration of new methodologies and technologies (preparation phase)</td><td>Fact finding and data gathering</td><td>Sharing and publication of data and information</td><td>Technical analysis of data and information</td><td>Determination of non-compliance</td><td>Political interpretation (post-processing phase)</td></tr>
<tr><td rowspan="2">Without relation (e.g. treaty or verification is non-existent but a norm)</td><td rowspan="2">Specialised scientist</td><td colspan="2">Whistleblower
(e.g. M. Vanunu)</td><td colspan="2">e.g. ZNF-analysis of the North Korean nuclear tests</td><td rowspan="4">Experts for the nuclear weapons control regime,
Technical specialised non-governmental organisations</td></tr>
<tr><td>e.g. seismic stations</td><td>e.g. seismic networks</td><td>e.g. seismologists</td><td rowspan="3">Arms-control specialists
specialised think tanks and networks</td></tr>
<tr><td rowspan="2">Indirect connection (e.g. distributed via open source)</td><td rowspan="2">Scientific publications
Commercial available technologies</td><td colspan="2">Whistleblower</td><td rowspan="2">e.g. ISIS satellite images
e.g. radionuclide experts</td></tr>
<tr><td>e.g. commercial images
e.g. radiation protection laboratories</td><td>Illegal information transfer (e.g. Wikileaks.org) Non-governmental organisations with access to information e.g. NCRI</td></tr>
<tr><td rowspan="2">Informal interaction</td><td rowspan="2">Specialised associations and networks e.g. iGSE, ESARDA, INMM</td><td colspan="2">Defectors</td><td rowspan="2">?</td><td rowspan="2">technical advice</td><td rowspan="2">Lobbying and technical advice</td></tr>
<tr><td colspan="2">Potentially NCRI as well</td></tr>
<tr><td>Official contribution or mandate</td><td>e.g. GSE, ISS, national support programs for the IAEA</td><td>non existent</td><td>Non existent</td><td>Non existent</td><td>Non existent</td><td>Non existent</td></tr>
</table>

Table 1: Classification of civil society actors in regard of the affected safeguard stage and the degree of integration with official procedures

Working Groups activities

Activities of the ESARDA Working Group on Standards and Techniques for Destructive Analysis (WGDA) in 2010-2011

Report of WGDA chair and vice-chair Yetunde Aregbe and James Tushingham

In the aftermath of the Nuclear Security Summit and the 2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), the European Union confirmed its view to strengthen the NPT as the cornerstone of the international nuclear non-proliferation regime, favouring a balanced approach between its three pillars: non-proliferation, disarmament and peaceful use of nuclear energy. Furthermore the international initiative on a holistic Safety, Security and Safeguards ("3S") concept for nuclear energy was launched with the Nuclear Safety and Security Group (NSSG) at the G8 summit in 2008, and is converging more and more towards the idea of internationally binding security and safety standards [1].

The objective of the ESARDA Working Group on Standards and Techniques for Destructive Analysis (WGDA) is to provide the Safeguards Community with expert advice on relevant standards, destructive analysis methods and procedures and their capabilities in support of Nuclear Material Accountancy and Safeguards. The WGDA addresses measurement issues arising from new challenges in safeguards and in related areas by (i) supporting the development of DA methods; (ii) determining the reliability of DA methods by promoting the use of appropriate quality control tools, including inter-laboratory measurement evaluation programmes; and (iii) recommending and promoting target values for uncertainties in measurements of nuclear material. In particular, the WGDA increasingly supports activities for the development and improvement of methods for the determination of nuclear signatures in environmental and "special" samples, emphasising the technical convergence of nuclear safeguards, nuclear forensics and nuclear security.

Currently, the ESARDA WGDA consists of 72 members from European and international safeguards authorities, nuclear plant operators, nuclear measurement laboratories, research institutes and universities. The ESARDA WGDA adopted the new Action Plan and Success Indicators (APSI) 2010-2012, which defines a multi-annual work programme for the WGDA. In addition to the objectives related to the terms of reference, the evaluation of synergies with the new ESARDA Novel Approaches / Novel Technologies Working Group NA/NT was included in the APSI.

1) Main activities of the WGDA in 2010

Revision of The International Target Values

The International Target Values for Measurement Uncertainties in Safeguarding Nuclear Materials (ITVs) are uncertainties to be considered in judging the performance of analytical techniques applied by industry to nuclear material subject to safeguards verification. The IAEA adopted the concept of ITVs in the early 1990's from the ESARDA WGDA. In 2010, the WGDA contributed to the revision of the ITVs, holding a dedicated workshop and a joint meeting with the WG NDA to discuss the values for different method/material combinations as well as the consistency with the ISO Guide for the expression of Uncertainty in Measurement ("GUM"). The requirements of GUM were emphasised by the ESARDA WGDA and by INMM in a Consultants Group Meeting on ITV's, convened by the IAEA. As a result, the revised ITV2010 include a dedicated chapter on *GUM and the use of ITVs by measurement laboratories*. The International Target Values 2010 are now also expressed as relative combined standard uncertainties for utilisation by measurement laboratories. The ITV2010 are intended to be used by plant operators and safeguards authorities, as a reference to the quality of state-of-practice measurements achievable in nuclear material accountancy (*International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials, IAEA-STR-368, Vienna, November 2010*) [2].

ESARDA Reflection Group

The ESARDA WGDA was represented by the WGDA chair in the ESARDA Reflection Group 2010. This group drafted a recommendation document on the international and European context and trends in nuclear non-proliferation, safeguards, security, forensics, disarmament, knowledge transfer, external communications and their impact on ESARDA Research and Development activities towards 2020. The ESARDA WGDA provided significant input to the meetings and final report, including synergies with other measurement regimes.

Training and Education

The WGDA developed destructive analysis and nuclear forensics modules for training and education. These are regularly presented at the ESARDA academic course on Nuclear Safeguards and Non-Proliferation and the Belgium Nuclear Education Network (BNEN) advanced course on safeguards, which are recognised by the European Nuclear Higher Education Network. In 2010, the essay by M. Sturm, *Destructive Analysis: Effective Analytical Support to Nuclear Safeguards and Non-Proliferation,* was selected as best student's paper of the 6th ESARDA course on Nuclear Safeguards and Non-Proliferation and published in the ESARDA Bulletin [3].

2) Main activities of the WGDA in 2011

Workshops on dedicated topics

The WGDA establishes exchange beyond the safeguards community via workshops on dedicated technical topics. One of the most powerful tools to detect undeclared nuclear activities is the particle and bulk analysis of environmental samples. Bulk analysis of the collected swipe samples using Thermal Ionisation Mass Spectrometry (TIMS) or Multi Collector-Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) may be used, whilst methods for investigation of single particles can improve significantly the ability to draw safeguards conclusions from swipe samples. Nowadays, alongside other techniques (e.g. Secondary Ion Mass Spectrometry, SIMS), ICP-MS combined with laser ablation (LA) sample introduction offers the potential for investigating the isotopic composition of uranium and transuranium elements in single particles. The ESARDA WGDA, in close collaboration with the Hungarian Atomic Energy Authority (HAEA), organised a dedicated workshop on 'Direct Analysis of Solid Samples Using Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS), held in conjunction with the ESARDA Symposium in May 2011. The final report of this workshop including recommendations was published in the ESARDA Bulletin No. 46, Dec. 2011 [4].

The WGDA organised, in conjunction with its annual working group meeting, a dedicated Workshop on *Uncertainties in Nuclear Measurements* from 8-9 November 2011 hosted by the International Atomic Energy Agency Safeguards Analytical Services (IAEA-SGAS) in Seibersdorf. Topics included uncertainty estimation from *state-of-the-art* to *state-of-the-practice* measurements, with a clear focus on exchange between reference measurement institutes, safeguards laboratories, nuclear and environmental material analysts and, in particular, operators. The aim was to investigate major contributions to the final measurement uncertainties that depend upon the material and technique applied; and to compare and discuss the different approaches in uncertainty estimation, including training. The ITV2010, as well as the consistency of measurements carried out by nuclear laboratories and by operators with the GUM approach, were another important topic.

Support to IAEA-ECAS

The IAEA Safeguards Analytical Services provide measurement services to the Department of Safeguards. Members of the ESARDA WGDA are closely involved, providing expert advice to support the project *Enhancing the Capability of the International Atomic Energy Agency (IAEA) Safeguards Analytical Service (ECAS)*.

ECAS comprises:

- The Large Geometry Secondary Ion Mass Spectrometer (LG-SIMS) and Clean Lab Extension (CLE)
- The new Nuclear Material Laboratory (NML)
- The Seibersdorf site infrastructure and security improvements
- Expanding the Network of Analytical Laboratories (NWAL)

The ESARDA WGDA focus is particularly oriented towards the new Nuclear Material Laboratory (NML) but also includes the provision of scientific and technical advice to facilitate support from the European Union and Member States. The WGDA chair and/or vice-chair participated in all relevant workshops and expert meetings held by the IAEA in 2010/2011 and will continue participation in 2012 [5].

ESARDA/INMM

The WGDA was represented by Y. Aregbe in the joint ESARDA/INMM workshop, October 2011. Members of the WGDA presented in the session on *Future Directions for Safeguards and Verification Technology and R&D* challenges for development and provision of metrological quality control tools in nuclear safeguards and security; progress in environmental sampling and analysis and advances in nuclear forensics; The WGDA Action Plan is perfectly in line with future developments for European and International Safeguards, Safety and Security systems. The emphasis that the ESARDA WGDA puts on education and training has been identified as a priority to guarantee knowledge transfer in the nuclear field. More information is available via: http://www.inmm-esarda-aix2011.com/

Publications

The ESARDA WGDA contributed in 2010-2011 with publications to the ESARDA Bulletin, related to analysis of nuclear material, nuclear safeguards and forensics, amongst them one publication on development of plutonium spike reference materials selected for the peer reviewed section [6]. Furthermore, the ESARDA WGDA technical sheet on COMPUCEA for on-site accountancy verification was published [7]. The technical sheet on coulometry has been accepted by the Editorial committee of ESARDA and is anticipated to be published in the ESARDA Bulletin, 2012. The ESARDA WGDA vice-chair is also a member of the ESARDA Editorial Committee.

Outlook 2012

WGDA proceeding papers from the 33rd ESARDA annual meeting (Budapest 2011) were selected for publication in the peer reviewed section of the ESARDA Bulletin in 2012. The final report of the dedicated Workshop on *Uncertainties in Nuclear Measurements* will also be published in the next ESARDA Bulletin. The WGDA will draft technical sheets on Hybrid K-Edge, on sampling and on analysis of environmental samples, on gravimetry and on uncertainty calculations to summarise the GUM approach. Overall, the WGDA has progressed well in 2010/2011, along the lines defined in the Action Plan, and succeeded in bringing experts from safeguards authorities, industry and research together to exchange views on selected topics on advances and developments in R&D and nuclear metrology. Within the Working Group on Standards and Techniques for Destructive Analysis, ESARDA is currently keeping abreast of methodologies applicable in the fields of nuclear safeguards, security and forensics.

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Guidelines for the development of sealing systems (WG on Containment and Surveillance)

prepared by M. Chiaramello[1] on behalf of the ESARDA Working Group on Containment and Surveillance
[1] Joint Research Centre of the European Commission, Ispra (VA), Italy

1. Introduction

In December 2000, the European Safeguards Research and Development Association (ESARDA) Scientific Committee Co-ordination Board (SCCB) held a meeting jointly with the Convenors of the ESARDA Working Groups. Among others, the participants discussed work plans and Terms of Reference.

The SCCB encouraged the Working Group on Containment and Surveillance (WGC/S) to take the lead in preparing a guidelines document on sealing systems to support new safeguards requirements. A first guidelines set was done for the Unattended Remote Monitoring and Measurements System (URMMS) in 2005.

These guidelines are intended for seals developers who may not be specialists in safeguards issues. They focus on the specifics of safeguards as compared to other security applications and are not intended for inspectors who are already well aware of all these topics.

The Euratom Safeguards DG ENER-E and the International Atomic Energy Agency (IAEA), (referred to collectively as the Inspectorates), pursue the concept of using sealing techniques for reducing on-site inspection effort at declared nuclear facilities. This concept had been proposed by the WGC/S in 1992 for the purpose of improving the cost-effectiveness of routine safeguards by reducing inspection time in the field. It also reduces the burden on operators and nuclear radiation exposure of inspectors and technicians. In fact, once nuclear material is put under sealing, inspectors do not need to check the material itself. The seal state indicates whether or not the continuity of knowledge of the sealed item is maintained.

Recent developments have allowed the Inspectorates to make wider use of sealing techniques and methods. To be acceptable for safeguards applications, equipment must comply with agreed standards. These standards are addressed in the remainder of this document. Chapter 2 discusses first general aspects of the standards, and Chapter 3 gives an overview of the guidelines. Essential requirements are addressed in Chapter 4.

2. General Remarks

The large variety of nuclear facilities to be safeguarded requires a great flexibility on the part of the Inspectorates in designing facility-specific safeguards equipment systems.

Safeguards equipment systems are combinations of customised and commercial-off-the-shelf (COTS) components. Safeguards-specific requirements, such as high reliability and high security, necessitate customised solutions for hardware and firmware in the sensitive parts of a safeguards system, e.g., the seals themselves and seal-reading equipment. In other parts of the safeguards system the use of COTS components helps to reduce procurement costs for hardware, software, training, and maintenance.

It is expected that remote data retrieval will enhance the technical possibilities of reducing on-site inspection effort. The precondition is, however, that the retrieved data are authenticated and encrypted and can be evaluated at headquarters. There must also be an overall cost benefit improvement compared to each current safeguards approach under consideration; i.e., the implementation of remote monitoring systems requires cost-benefit analyses on a case-by-case basis.

It is difficult to assess the investment costs for remote monitoring, given that technical progress leads to new concepts and requires periodic replacement of safeguards equipment. Reduction of on-site inspection effort results in cost savings, whereas data communication encounters costs. Communication costs may vary significantly from one country to the other; in addition, the Inspectorates may face investment costs for communication infrastructure. Depending on the communication technique and the number of facilities involved, the Inspectorates may not be able to transmit data to the desired extent. Regarding the use of encryption algorithms for authentication and encryption, the situation may become more favourable, because it is expected that algorithms are available free of charge. Archiving requirements and evaluation effort may be identical for systems with and without remote data retrieval.

In some types of facilities inspection effort can be reduced by the facility operator performing safeguards relevant activities. For instance, transport and storage casks with spent fuel can be sealed under camera surveillance with seal-video interfacing approved for safeguards use.

3. Guidelines Overview

3.1. Sealing systems

A sealing system is generally composed of two basic elements, the seals themselves and procedures and/or equipment to verify the seals. Seals perform two main functions: identification (and/or authentication) of the seal itself and indication of the seal's integrity (usually via a non-erasable feature that keeps track of attempts to break into the seal). Identification need not be unique, but it must not be possible that two seals with the same identification be used at the same place. Therefore, unique identification of individual seals is preferable. This identification is often called the fingerprint of the seal.

3.2. Seals

There are two types of seals, active and passive. Active seals have electronics which allow continuous monitoring of the seal (and of a closing mechanism if present). Passive seals are intrinsically more reliable in the long term, but they typically require manual verification.

The main advantage of active seals is continuous monitoring of the seal and sealing mechanism. Continuous monitoring can be literally continuous or periodic, with a frequency such that no attack against the seal can be successfully accomplished between monitoring periods. Active seals can be adapted for remote monitoring by adding secure communications to the system.

Disadvantages of active seals stem from the frequency of monitoring and the electronics inside the seal. The frequency of monitoring affects the lifetime of the seal, making it necessary to replace seals regularly. Energy requirements of active seals introduce the necessity to change batteries regularly. The electronic content of active seals makes them susceptible to electromagnetic interference and difficult to apply in some environments, notably, under water. All of these drawbacks may constitute reasons to consider frequent manual verification of a passive seal rather than active monitoring.

A significant advantage of passive seals is their reliability for long-term application without intervention. Depending on the technologies employed, some seals (e.g., metal cup seals and ultrasonic seals) are virtually insensitive to aging. However, optical fiber seals can be sensitive to radiation and therefore need to be changed regularly. The main inconvenience of passive seals is that inspectors must be physically close to the seal for seal verification. Upon inspection, a broken seal does not indicate when it was broken, only that it happened between previous inspection and the current one. Metal cup seals cannot be verified in-situ, and inspection requires the removal of the seal and the installation of a new one. Verification of these seals is performed later by a verification laboratory at Inspectorate headquarters. Remote inspections are not always possible and may result in allowing the operator to have access to the seal reader (see Section 3.3). Ultrasonic seals are the only type currently suitable for underwater use.

3.3. Seal-reading equipment

Most of the time, seals require a specific reader system to control them. The reader can be left in the custody of the site when it is dedicated to a particular plant (e.g., an ultrasonic reader), or it can be transported in and out of the site by the inspectors. In the case of metal cup seals, the reader cannot be transported by the inspectors and is available only at headquarters.

Particular attention must be given to the sensitivity of the data required for the control of readers stored onsite or readers transported by the inspectors. Typically, inspectors must arrive for an inspection with a copy of the original fingerprints to be used by the readers only at the time of inspection, so that sensitive information is never stored inside the devices. The original fingerprints must never be loaded onto the hard disk of the controller computer. The system must use external memory support carried by the inspectors. If the data are loaded on the hard disk, a trace always remains even if they are later deleted. Complete erasure would require the entire disk to be overwritten.

Computers or reading equipment must never be left unattended, and they must be sealed when stored in the facility.

It is conceivable that readers could be remotely controlled from headquarters. This would require authentication of the readers themselves and separation of the functions they perform. In such a case, readers must only read the raw data and transmit the data correctly encrypted and authenticated. Analysis of the data and comparison with the original fingerprints is done at headquarters. The reader left in the operators' hands must contain no sensitive data and must be monitored periodically by the inspectors for intrusion or tampering. A good practice is to have inspectors exercise the readers periodically, including some incorrect operations. This would allow validating the actual inspection process and that the equipment has not been modified to give erroneous results.

3.4. Commercial-Off-The-Shelf (COTS) components

Many system components, such as communication links, microcomputers, and data collection systems, are not security relevant and may be COTS products. Failures and mains power outages do not result in a loss of unrecoverable data. These components could be serviced, repaired and replaced by commercial contractors.

3.5. Approval for routine inspection use

Given the safeguards-specific requirements, it is necessary that prior to acceptance as equipment authorised for routine inspection use the systems must successfully pass the following evaluations:

- Acceptance testing
- Field testing
- Specific qualification testing, including radiation testing[1]
- Third-party vulnerability assessment of sealing system (not only the seals).

4. Essential requirements and recommendations

4.1. Environmental conditions

One of the environmental conditions that must be addressed is the level of radiation to which the seals are exposed and the way radiation can affect them. The adverse effects of radiation can result in periodic replacement of the seal. Replacement due to radiation effects must be planned.

The temperature range for the seal in a given application must also be considered. Extreme low or high temperature will affect battery capacity and energy consumption. Some parts of the seals may also be affected.

If not specifically designed for underwater application, seals may require complicated arrangements to keep part of the seal accessible from pond sides.

Electromagnetic radiation (EMR) susceptibility and humidity (if not intended for underwater deployment) must also be considered during the development.

The seals, tools, and control equipment must be considered separately when evaluating the effects of environmental conditions. The seals must withstand site environmental conditions for all of their active life, while tools and control equipment are only exposed during inspections (e.g., a few hours a month).

4.2. Operator constraints

Operator constraints to be considered include the following:

- Power supply availability and characteristics
- Accessibility around the sealed items for the inspector and equipment
- Limitations on the types of materials allowed inside a specific part of the plant
- Whether RF is allowed and compatible with site operations (if seals use RF)
- Whether the seal can be operated by inspectors alone or require operator staff assistance.

In addition, the day to day operation of the facility must not be impacted by the desired installation, unless impacts are negotiated with the operator. Seals should be applied in a manner to avoid unintentional damage to the seal.

4.3. Operational conditions (from an inspection point of view)

The following requirements are concerned with the use of the sealing system in inspection activities:

- Accessibility of the sealed items and of the seals. It is not always possible to access the sealed parts easily, such as in some dry storage facilities. This also affects the frequency of replacement (due to seal vulnerability to environmental issues as noted in Section 4.1).
- Operational conditions, including type of item sealed and the safeguards requirements of the sealing operation. This is important in determining the frequency of controls.
- The duration of seal deployment. This is particularly important if sealing operations, including attachment, verification and removal, are difficult to perform or the seal is in a hazardous area.
- Handling of the associated equipment. Is the equipment brought every time by the inspectors or is it stored in a safe place close to the inspected area or at least on-site?
- Handling of unused seals. Are they stored in a secure place on-site or are they brought in by the inspector? How are removed seals managed? Removed seals are a security vulnerability if unauthorized personnel have access to them and can reverse-engineer them.
- Seal data. Is it conceivable to have seal data stored on-site as long as it is not on the computer used for the control? Or is the data always removed from the site by the inspectors? What are the consequences if inspectors perform a seal check before the last check has been updated?
- Database location. It would be good practice to have all databases centralized in the headquarters and not to let any data into the facilities. But in some facilities, inspections are very frequent, and it may happen that an inspector goes there before a last inspector has updated the central database. The new inspector will then use out-of-date data for the inspection. In this case a local database in the facility would resolve the problem, but it must be carefully protected (specific room, specific computer).

[1] So far the IAEA and Euratom have cooperated under the Euratom Support Programme to the IAEA at the Joint Research Centre at Ispra, applying agreed test procedures (JRC Technical Note No. I.96.77). Radiation testing has not been routinely performed but will be requested in the future.

Occasionally an inspector may forget to download the data before leaving headquarters, or may add an inspection to the mission. In this case having a copy of the data in the facility may save the mission. Of course this copy must be carefully stored to prevent disclosing it to unauthorized personnel.

- Verification. When possible, the system should be designed to allow automatic verification of the seals and/or remote monitoring and verification. This functionality may require some further development, but the sealing method may allow this possibility to be conceived in the (near) future.
- Authentication and encryption. A clear procedure on the management of the encoding keys must be established. This procedure must take into account the fact that multiple inspectors may use each piece of equipment, none of whom have in-depth knowledge of the equipment itself or principles of data security

4.4. Other characteristics

The following issues are not directly correlated with the operation of the seals but have impacts on the system as a whole.

- Maintenance of the seals and associated equipment. Sometimes it is possible for inspectors to repair the equipment on site, if specialized knowledge is not required. In case this is not possible, it is not guaranteed that equipment that entered the controlled area can leave, depending on its level of contamination and the ability to decontaminate it. The longer the equipment stays in a controlled area, the less likely it is that it can be removed. The developer must have this in mind when developing new equipment. It is better to have spare parts, easy to change by non-specialists, immediately available (stored in the inspector office for instance), rather than a closed system than can only be maintained in the manufacturer's laboratory. Intervention by the manufacturer can also be very expensive, because nuclear plants are often in remote places and are not always easily accessible, and because entering controlled areas in a nuclear facility is allowed only to specially trained personnel.
- Inspector-friendly design. Inspectors may not be specialists in any given sealing system but must be able to operate it correctly. The system must, therefore, guide the inspectors in their job and help them avoid all the potential vulnerabilities. This requires detailed procedures, user-friendly software design, and specific training.
- Transportation of seals and equipment from headquarters to the facility. Some seals can be difficult for the inspectors to carry in a mission due to their weight, volume, and number required. Transportation issues include the limitation of some substances, such as lithium ion batteries, in airfreight.
- Neutron activation. Neutron activation is an issue for batteries (although it may be more relevant to testing than in operational use).
- Interface between the sealing system and the Inspectorate management system or database. There may be issues related to the ownership of the database and its management as it relates to the sealing system.
- Life-cycle cost. A more expensive seal that does not need frequent maintenance or replacement can give more value over time than a more economical seal that needs to be replaced several times during the expected safeguard life of the seal. This issue should be considered on a case-by-case basis.
- Reliability and confidentiality of suppliers over the expected period of use.

4.5. Review of similar applications (if any) and existing seals

When considering a new sealing application, a primary consideration is whether existing sealing systems are already available and used in similar applications. If so, can the existing system be considered for this new application, and how does the new application differ from existing ones?

A critical review of the advantages and the disadvantages of existing sealing systems, in view of the specific application considered, must be done before starting implementation.

It is useful to analyze what does not work well with existing systems in similar applications. Such analysis is useful to avoid repeating the same errors or, possibly, to improve the use of a given sealing system.

4.6. New development

Sealing systems are never static, and it may become necessary to develop a new sealing system or at least to make some substantial modifications to existing systems. Reasons for doing so can be to reduce the cost of the systems, accommodate advancing technology (both for the seals and for the potential adversary), and improve sustainability of the existing systems.

The following points must be considered when developing a new sealing system or adapting an existing one:

- Mechanical interface with the seals. This consideration regards how the seal is attached to the item to be sealed. It is also important to consider operator constraints, including what materials can be used, and what materials have been refused.
- Tools for seal operations. These include the tools needed to handle the seals and the operator or plant constraints regarding the use of these tools. For example, is the inspector allowed to manipulate the tools, or is it required that it has to be done by the operator staff?

- Control equipment. It needs to be determined if the control equipment is to be transported to and from the site by inspectors, transported from headquarters for each inspection, or left in a safe place on-site. Another determination to be made is whether an adequate power supply is available at inspection place or whether battery powered equipment should be considered.
- Inspector interface. Procedures for how to use the sealing system are required. This same need applies to any application-specific software.
- Management interface. How and what to communicate with headquarters should be defined. Some possibilities are inspection results only, raw data, elaborated data, level of security, and time-bounded communication (i.e., is real-time communication necessary or is it acceptable to have communication delayed?).
- Security of the seals, tools, control equipment, communication, and removed seals.

4.7. Replacement of existing system

It may be occasionally necessary to replace an existing system. There can be several reasons for considering this operation, and it must be approached carefully.

The reason(s) for the change must be well recognized. An analysis of the existing system must be done to identify its advantages and the disadvantages.

To successfully replace a sealing system it is often necessary to change as few of the inspection procedures as possible, so that transition from the existing system to the replacement system will be easier. When possible, it is recommended that most of the existing tools be reused, so that operators' and inspectors' working habits are not changed too much.

New functions that are implemented as a result of the changes must not represent more workload for the inspectors and/or operators, but should simplify the use of the sealing system. Not all new functions may be used at the introduction of the new system.

4.8. Planning

Some words about planning seal development!

To be successful, seal development must be planned carefully. Some steps in this development process can be very time-consuming, and this must be kept in mind when developing new seals or substantially modifying existing seals.

The first points to consider are the mechanical interface requirements. They need to be agreed upon between the developer and the Inspectorate, and should also be reviewed by the operator.

Eventually, during the design phase, the seals must be tested in the laboratory under conditions as close as possible to the real ones. These tests may raise some vulnerability aspects that can be handled by correct procedures.

During the laboratory tests, the inspector and data management interfaces can be defined. The development can be done independently of the laboratory tests and/or the finalization of seal manufacture once the laboratory tests are successfully completed.

When the first seals and the associated reading equipment have passed the tests successfully, procedures and software can be developed, and the field trials can be done. The field trial permits testing the seals in real conditions together with the associated tools, control equipment, management, and operation procedures. The field trial must cover all aspects of the seal life cycle (attachment, verifications, and removal). At the end of the field trial, the sealing system would be ready to be deployed.

There is still an important step to complete before the seal system implementation can become operational. A full vulnerability assessment must be performed by a third-party laboratory (i.e., independent from the developer and from the end-user) to identify all the potential vulnerabilities, their importance, and the countermeasures that can be taken to address them. In case of adaptation of an already approved system, a vulnerability review can be performed that covers only the modified elements of the system. This vulnerability assessment takes one to two years, so it may be useful to have some third-party vulnerability review done just after the laboratory tests and in parallel with the field tests.

It is good practice to have an operational review after one year of deployment. Following use of the system for a time, some adaptation of software or procedures can be discussed to improve its utility.

Report on the 2011 INMM/ESARDA Workshop: The future of Safeguards and Non-Proliferation

Ken Sorenson, INMM Vice President
Jim Larrimore, INMM International Safeguards Technical Division Chair
Michel Richard, INMM Senior Member, ESARDA Verification Technologies and Methodologies WG chair and CEA

IAEA Safeguards State Level Approaches, SSACs, RSACs, triple-S culture, safeguards by design, monitoring and verification, detection of undeclared activities, open sources, nuclear disarmament verification , global zero, synergies between treaty regimes, and education and training etc. These were just a few of the terms discussed in depth at the 7th INMM/ERSARDA Joint Workshop entitled; Future Directions for Nuclear Safeguards and Verification, held in Aix-En-Provence, France, Oct. 17-20, 2011.

Each INMM/ESARDA joint workshop chooses a particular theme associated with safeguards, verification, and non-proliferation. With the advent of the growing interest in the commercial fuel cycle, movement to reduce existing weapons stockpiles with the prospect of a fissile material for nuclear weapons cut-off treaty, advancing technical and facility capabilities of non-weapons states, and the severe accident at Fukushima coupled with the diverse response to this accident, the focus for this 7th joint workshop on "looking to the future" in safeguards and verification R&D was timely. Jim Larrimore and Michel Richard teamed together as workshop chairmen to structure a program that sought to develop a deeper understanding of the rapidly changing and complex issues we are facing today and must address in the near-term future.

The workshop consisted of four parallel working group sessions with opening and closing plenary sessions serving as bookends. The four working groups and their chairs were:

- Future Directions for International Safeguards
  - Jim Casterton (IAEA) and Paul Meylemans (EC); co-Chairs
- Future Directions for Safeguards & Verification Technology and R&D
  - Diana Blair (Sandia Nat'l Labs) and Sergey Zykov (IAEA); co-Chairs
- Broader Perspective on Non-proliferation and Nuclear Verification
  - Mona Dreicer (Pacific Northwest Nat'l Lab) and Gotthard Stein (Germany); co-Chairs
- Education and Training
  - Willem Janssens (EC) and Debbie Dickman (Pacific Northwest Lab)/Melissa Schultz (DOE/NNSA)

The co-Chairs of the four working groups were tasked to put together the speaker program, lead the sessions, and report out during the Closing Plenary. The speakers that attended were top professionals in their fields, which stimulated and enlivened the discussions. To summarize two and one-half very full days: the International Safeguards Working Group recognizes the IAEA lead to work towards a State Level Concept of management and oversight of international safeguards; the Safeguards & Verification Technology and R&D Working Group identified traditional, as well as non-traditional concept, hardware, and software approaches to monitoring and verification; the Non-proliferation and Nuclear Verification Working Group discussed at length the nuclear regimes and their interplay amongst all the states involved, weapons states as well as non-weapons states; and the Education and Training Working Group took up where they left off in Tokyo at the 6th joint workshop (2008) with a strong list of actions to further develop this important area. One aspect that was common in their list of Action Items was the need for INMM and ESARDA to work together in this area.

The Opening Plenary put the focus of the workshop in context for the rest of the week. Herman Nackearts, Deputy Director General of the IAEA Safeguards Department, provided a frank history of IAEA implementation of safeguards and identified concrete suggestions for moving forward in the future to make international safeguards more effective and efficient. Mr. Nackearts talk was followed by Piotr Szymanski, EC/Directorate General for Energy, Director, head of Directorate for Nuclear Safeguards who described the role of EURATOM in NNWS and NWS European Union Member States and stressed the importance of the cooperation between EURATOM and the IAEA, Philippe Delaune and Etienne Pochon, both of CEA, who presented perspectives on international safeguards from an active IAEA and EU-member country.

The Closing Plenary began with a report out by the Chairs of each Working Group. Without much direction and with little time, each report was succinct and provided a good overview to the general assembly of the working group discussions. This was followed by a compelling talk from Jacques Ebrardt, CEA, entitled: Dismantling the fissile materials production plants for nuclear weapons: a French Perspective. This talk covered the entire dismantling and restoration of the French materials production capability and the French nuclear testing site in the South Pacific; starting from the two atmospheric test sites in the Pacific, to the uranium enrichment facility in Pierrelatte, to the three Pu production reactors and associated reprocessing plant in Marcoule. Mr. Ebrardt stressed that this commitment by France was unilateral, transparent, and irreversible.

From an INMM perspective, this workshop highlights the importance of our relationship with ESARDA. INMM attendees at this meeting included the Vice President, three members of the EC, the Chair of the Technical Division Oversight, the Chair of the International Safeguards Division, and the Chair of the Non-proliferation and Arms Control Division. Of course, there were also numerous INMM members that attended and participated, many of them ESARDA members who are also INMM members.

Recognizing the importance of the INMM/ESARDA relationship, an initiative began last May to develop a more formal relationship between the two bodies. A sidebar meeting was held at this workshop to finalize a draft Letter of Intent (LOI) that provides a more stable framework to strengthen and expand our working relationship. This LOI still must go through both governing bodies for approval. Stay tuned for further developments.

One other development of note that occurred at this workshop was the establishment of a new INMM working group under the International Safeguards Division that will focus on geospatial and open sources as technologies that need to be addressed in the future of safeguards and verification.

In conclusion, the workshop was a tremendous success. Thanks to ESARDA, the CEA and the JRC for sponsoring the workshop and for the workshop chairs for putting together and staging such a timely and productive meeting. The future of international safeguards and verification is now and the need to act is compelling.

Report on Stand-off Detection Technologies meeting organized by the Esarda Na/NT and NDA WGs in Helsinki

Harri Taivonen

Introduction

The European Safeguards Research and Development Association (ESARDA) Working Group (WG) on Novel Approaches and Novel Technologies (NA/NT) was established in 2010 to provide expert advice and assistance to international nuclear inspectorates on novel approaches and technologies. The WG targets appropriate technologies that have the potential to improve early detection, efficiencies and effectiveness of inspection, monitoring and verification methods for safeguards, nuclear security and verification of international treaties involving nuclear disarmament, arms control and non-proliferation. The NA/NT WG currently comprises over 50 members, including representatives from the IAEA, Euratom and CTBTO. At the ESARDA meeting in Budapest (May 2011[1]), the NA/NT WG, together with the ESARDA Non-destructive Analysis (NDA) WG, agreed to collaborate in joint scientific sessions on the topic of stand-off detection technologies[2].

The Meeting on Stand-off Detection Technologies was hosted by the Finnish Radiation and Nuclear Safety Authority (STUK) in Helsinki, Finland on 28 and 29 September 2011. Both WGs met in joint scientific sessions on the first and half of the second days. Both WGs arranged also their own half-day sessions to deal with on-going group-specific issues. In addition to the two-day meeting, STUK organized a laboratory tour on Friday 30 September 2011 and provided a field demonstration of a nuclear security mission, including a demonstration of its “Reach-back” services.

The overall aims of the joint WG meeting were the following:

1. Consideration of scientific and technological innovations that have the potential applications meeting current and future safeguards challenges,
2. Establishment of contacts between participant end-users in international verification and non-proliferation organizations and leading R&D experts in new and novel technology areas, and
3. Introduction of the IAEA Safeguards Department’s Long-Term R&D Plan.

The meeting portion of the programme was divided into five topical sessions, each addressing one of the following subjects:

- Shielded nuclear material,
- Neutron detection and measurement techniques,
- Optical stand-off detection techniques,
- Spent fuel verification and
- Antineutrino detection.

An important general aim of the meeting was the establishment and further fostering of closer cooperation amongst scientific and engineering experts and potential end-users in international treaty verification organizations regarding novel approaches and technologies. Novel technologies, by their very nature, create additional challenges for the inspectorates, which must match needs against a wide set of potential novel solutions, typically without the benefit of an already established network of experts and suppliers, as is the case with more traditional technical areas including surveillance, containment, gamma and neutron measurements, material accountancy, and satellite imagery. On one hand, the inspectorates may not necessarily have deep understanding on what technologies are available, or could be developed to fulfil the safeguards needs. On the other hand, scientific and technical experts may not be cognisant of international verification practices and needs. The establishment of the NA/NT WG provides a practical bridge between the scientific community of experts and potential technology users in the international treaty verification organizations.

Meeting Summary

The meeting was opened jointly by the Chairpersons of the NA/NT WG, Harri Toivonen, and the NDA WG, Anne-Laure Weber. Mr Toivonen welcomed all participants and outlined the meeting’s aims and topics. He stressed the benefits of meetings, like this one, as they provide opportunities for a wide range of expertise to gather and address particular topics of interest to users in verification organizations, particularly in the areas of nuclear safeguards and security, weapons disarmament verification, and Comprehensive Nuclear Test-Ban-Treaty verification.

[1] A novel approach or technology has not been applied routinely in a detection of verification role

[2] Stand-off detection technologies include a wide range of methods that are capable of measuring physical phenomena at a distance from the entity of interest

Anna-Marie Weber also welcomed participants, stressing the importance of the joint meeting as a means of developing cooperation between the NA/NT and NDA WGs. Ms Weber highlighted areas of possible cooperation, such as novel neutron detection techniques.

Over the two days of meeting, 17 presentations were provided to the participants (see titles and authors in list of abstracts). The meeting agenda, presenter abstracts and their respective PowerPoint presentations, can be found at the NA/NT WG CIRCA website[3]. Alternatively, abstracts and presentations can be requested directly from the NA/NT WG Scientific Secretary, Mr Julian Whichello at: j.whichello@iaea.org.

The NA/NT WG focused its own meeting to listening the plans and needs of the international organizations. The following presentations were given:

- J. Whichello, Long-Term R&D 2012-2023
- M. Nikkinen, CTBTO Issues on the ESARDA NA/NT Including Lessons Learned from Fukushima Accident
- P. Schwalbach, Safeguards Instrumentation: Needs and Wishes

The presentations were an useful opening to the dialog between safeguards needs and research capability in the universities. Further work is needed to get together the inspectorates and the scientific community.

The agenda of the NDA WG was as follows:

- Gamma spectrometry (P. Peerani)
- ESARDA Waste Performance Values (J. Rackham)
- MCNP Multiplicity Benchmark (A. Weber)
- Neutron detectors for He-3 replacement: (K. Boudergui)
- Development of methods/benchmarks for use of modelling (MCNP or others) to calculate spectra (P. Chard)
- Guidelines for developing unattended and remote monitoring and measurement systems (P. Peerani)

Field exercise demonstration and organized laboratory tour at STUK

On 30 September 2011 all participants of the meeting and additional guests were invited to observe a field demonstration of a mobile radiation measurement system and to tour the STUK R&D laboratory for Security Technology.

The demonstration modelled a nuclear security related-incident centred around the location and identification of hidden radiation sources. By initially scanning a specific (roughly 1 sq. km area), the field teams were able to detect and then to localize the radioactive sources, and identify the isotopes involved. For this purpose, a radiation measurement vehicle (SONNI) was used, further supported by two nuclear security personnel wearing portable radiation scanners (RanidPro200 backpack systems), and a data management system for in field measurements (SNITCH). The data evaluation at the simulated control room was performed using the results of the Vasikka software (included with the detection equipment) and with more advanced software tools based on multiplet fitting and hypothesis testing. All data were available in real time at the control room (delay 4 seconds).

Information, which included the vehicle and personnel positions, neutron and gamma count rates, actual gamma spectra and pictures taken from cameras on the vehicle and hand-held cameras used by personnel on the ground, were transferred from the field via 3G or GPRS to the control room and displayed on multiple screens. There, a second evaluation of the received data took place by an expert support team, and further action plans were transmitted to the field teams via a dedicated police radio network.

After the demonstration, a tour of the STUK R&D labs was organized. In six separate locations within the laboratory complex, introductions and demonstrations on alpha detection and alpha-spectrometry, portal radiation monitor, non-destructive particle analysis system (PANDA), spectral portable radiation scanner (backpack RanidPro200), mobile radiation detection platform (SONNI), and a system for the production of Xe-133m gas were provided.

Meeting Outcomes

During its half-day meeting, the NA/NT WG decided to establish three subgroups to work on the following topics:

- Optical stand-off detection methods
- Stand-off detection of antineutrinos
- Novel methods for the verification of future arms control and disarmament treaties.

Coordination of the optical stand-off detection sub-group was accepted by Juha Toivonen, Tampere University of Technology. Coordination of the antineutrino sub-group was accepted by Muriel Fallot, University of Nantes. Julian Whichello (IAEA), Mika Nikkinen (CTBTO) and Ian Russel (AWE), proposed their joint coordination of novel treaty verification methods.

Conclusion

ESARDA WGs provide a useful foundation for addressing issues of importance to the international treaty verification community. Through its membership comprising both experts and end-users, the NA/NT WG works to create a deeper awareness of novel R&D activities taking place in other ESARDA WGs, national laboratories, private industry and academia, that will benefit the verification community in the medium and longer terms.

[3] https://circab.europa.eu/Members/irc/securejrc/jrc_esarda/library?l=/wg_nant&cookie=1

Titles of presentations made

Shielded Nuclear Material

M1 Overview of AWE programme into enhanced detection of shielded nuclear material
J. O' Malley

Neutrons

N1 Fast neutron detection using He-4 scintillation
R. Chandra, G. Davatz, U. Gendotti, and D. Murer

N2 Neutron gamma discrimination in standard plastic scintillators: application for passive neutron measurements
K. Boudergui

N3 NEDENSAA – a NuPNET neutron detector R&D project
H.T. Penttilä

N4 Neutron detection for border monitoring using NaI spectrometer at energy interval 3–8 MeV
A.-P. Sihvonen, P. Holm, K. Peräjärvi, T. Siiskonen, and H. Toivonen

Optics

O1 Optical remote sensing for stand-off detection and non-destructive analysis of atomic and molecular species
J. Toivonen

O2 Recent achievements on alpha imaging systems
C. Mahe

O3 Long and short range imaging systems for the remote sensing of alpha emitters through the detection of air fluorescence
V. Koslowsky, H.R. Andrews, H. Ing, M. Dick, P. Forget, E. Inrig, and L. Erhardt

O4 Imaging of alpha emitters
J. Sand, T. Nieminen, S. Ihantola, K. Peräjärvi, H. Toivonen, and J. Toivonen

O5 Position-sensitive gamma spectrometry of alpha emitters via alpha-induced UV
S. Ihantola, J. Sand, K. Peräjärvi, J. Toivonen, and H. Toivonen

Spent Fuel

S1 Recent theoretical and methodological results on analysis of 235U, 239Pu and 241Pu content in spent fuel
D. Chernikova, I. Pázsit, J. Anderson, L. Pál, S. Pozzi, V. Romodanov, and V. Sakharov

S2 Shipper/receiver difference verification of spent fuel by use of PDET
Y.S. Ham

Antineutrinos

A1 Antineutrino detection as a novel tool for reactor monitoring: an overview
M. Fallot and R.J. De Meijer

A2 Core reactor monitoring by an antineutrino detector (CORMORAD)
M. Battaglieri, R. De Vit, L. Faur, L. Ficin, and G. Firpo

A3 The NUCIFER experiment: reactor neutrino detection for non proliferation
L. Bouvet, S. Bouvier, V. M. Bui, H. Carduner, P. Contrepois, G. Coulloux, M. Cribier, A. Cucoanes, M. Fallot, M. Fechner, J. Gaffiot, L. Giot, F. Gomez, R. Granelli, G. Guilloux, T. Lasserre, L. Latron, A. Letourneau, D. Lhuillier, A. Marchix, J. Martino, G. Mention, D. Motta, Th. A. Mueller, N. Pedrol-Margaley, Y. Piret, A. Porta, G. Prono, C. Renard, L.M. Rigalleau, D. Roy, L. Scola, J. L. Sida, P. Starzynski, C.Varignon, and F. Yermia

A4 Nuclear reactor simulations for unveiling diversion scenarios: capabilities of the antineutrino probe applied to actual and Generation-IV reactor monitoring
S. Cormon, V.M. Bui, M. Fallot, J.-B. Clavel, L. Giot, B. Guillon, M. Lenoir, A. Nuttin, A. Onillon, A. Porta, S. Picot, N. Thiollière, and F. Yermia

A5 Feasibility of a very compact antineutrino monitor for reactors
R.J. de Meijer, M.W. van Rooy, and F.D. Smit

Report by the WG on Non Destructive Analysis

by Anne-Laure Weber

1. General Information

The ESARDA Working Group for techniques and standards for Non Destructive Analysis (NDA WG) provides the Safeguards community with expert advice on Non Destructive Analysis methods, procedures, reference material, and performances for nuclear material characterisation. The main tasks of the WG include (1) an expert advice and an assistance in the development and the implementation of new and improved NDA methods in support to new Safeguards requirements, (2) the determination of NDA methods'reliability, by coordinating intercomparison exercises and benchmarks and publishing performance values, (3) the identification of new needs and areas where R&D is required and accordingly, the promotion of either the procurement of new reference materials, or the development and use of new calibration and validation tools.

The NDA WG acts as a forum for the exchange of information on NDA methods, gathering 19 participants in 2011 from national, regional and international control authorities (IRSN, STUK, EC/ENER, ABACC, IAEA) together with nuclear plant operators (Sellafield Ltd, WAK-GMBH), NDA equipment suppliers (AREVA, Babcock In't Group, AMETEK) and R&D laboratories (EC/JRC, CEA, SCK-CEN, IKI, Chalmers University, AWE, LANL, LLNL, ORNL).

The NDA WG met twice in 2011: around the symposium in Budapest in May, and together with the NA/NT WG in Helsinki in September. The topics addressed during those meetings can be categorised according to four main technical fields:

- general functions of NDA instrumentation;
- evaluation of specific NDA techniques for Safeguards;
- NDA techniques for waste sentencing;
- modelling of NDA instruments.

Each of those topics were addressed in specific projects reported and discussed during the meetings. The on-going projects, and their progresses, are described into more in details in chapter 2. In particular, the WG completed in 2011 the project related to the evaluation of performance values for non-destructive assay Techniques applied to wastes.

The WG collaborates with other discipline-oriented WGs to exchange technical information on topics of common interest, or investigate synergies for the development of dual use instruments. A meeting on stand-off detection technologies was jointly organised with the NA/NT WG in Helsinki the 28&29 September 2011, with a specific NDA contribution to two sessions respectively dedicated to alternative technologies to ^{3}He for neutron detection, and spent fuel verifications. Such a meeting, also covering optical stand-off detection techniques and antineutrino detection topics, allowed the connection of end-users in verification and non proliferation organizations and R&D experts in new and novel technologies areas having potential applications to meet current and future safeguards challenges. The IAEA document "International Target Values 2010 for measurement uncertainties in Safeguarding nuclear Materials"[1], reviewed together with the DA WG in May 2010, was released last year by IAEA, and will be published in the ESARDA Bulletin. The URMMS (Unattended and Remote Monitoring and Measurement Systems) guidelines, developed together with the C/S WG and published in the ESARDA bulletin issue n°33, was reviewed last year following a joint C/S-NDA WGs meeting in October 2010.

The WG also contributes to the ESARDA course on safeguards and no proliferation, by giving lectures on neutron detectors (P. Peerani) and gamma spectrometers (R. Berndt).

2. Review of the on-going projects

General functions of NDA instrumentation:

The NDA WG has recently launched a new project related to the R&D currently performed on alternative neutron detection technologies for the replacement of ^{3}He due to its shortage, with applications in both nuclear security and safeguards. The objectives of such a project are (1) to provide a forum of exchange among the labs working on that topic, by mean of presentations on pending research programmes, (2) to foster collaboration between European labs and ESARDA members, (3) to benchmark and

[1] International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials, IAEA STR-368, November 2010.

evaluate the valuable techniques. Four presentations were given during the meeting on stand-off detection technologies on this topic, two of them being related to developments of instruments for passive nuclear material detection: fast neutron detection using ^{4}He scintillation (R. Chancra), NaI spectrometry at energy interval 3-8 MeV (A.P. Sihvonen); a third one on developments performed on neutron/gamma discrimination by signal processing in standard plastic scintillators for homeland security applications (K. Boudergui); and the presentation of a European project named NEutron Detector developments for Nuclear Structure, Astrophysics and Applications, aimed to improve neutron detection setups and concepts (H. T. Penttilä). The aim and work program of the FP7 SCINTILLA project, which will start in 2012 with the participation of several members of the WG as partners or advisors, also made the object of a global information. Its purpose is the development and testing of detection capabilities of low or difficult to be detected radioactive sources and nuclear materials, via scintillation materials and cadmium-zinc-telluride detectors.

Evaluation of specific NDA techniques for Safeguards:

In this area, the WG provides support to the international WG on gamma spectrometry techniques, jointly established by ESARDA and INMM, to address problems related to isotopic measurements of U and Pu with special emphasis on code sustainability, standardization and validation issues. The first project is related to the development of a testing platform for gamma evaluation codes, to be used by the developers for validation purposes and by end-users for performance evaluation purposes. The NDA WG substancially contributed to the definition of the database's structure, with a proposal of having three sections with spectra acquired with several detector types, dedicated to (1) spectra acquired in ideal measurement conditions in the typical range of application of the codes, (2) spectra acquired in non-ideal conditions such as poor statistics, poor resolution, too high count rates or strong attenuation, (3) spectra acquired outside the normal operation conditions, such as very high burnup samples, nearly pure isotopes samples, samples with high minor actinides content or presence of contaminants. An invitation to provide spectra, with a documentation specifying the expected type of spectra, format and acquisition data information has been sent to EU and US labs in 2010 in order to collect spectra. Approximately 200 spectra have been collected today, including the database from the ESARDA U-1995 and Pu-2000 exercises available on the ESARDA website, filling almost all of the measurement categories for germanium detectors, excepted some of the unusual cases. The next step consists in evaluating the quality of the collected spectra and selecting the valuable spectra to be included in the database, which will be hosted by a dedicated area of the ESARDA website.

NDA techniques for waste sentencing:

The WG has practically completed the project related to the evaluation of performance values for non-destructive assay Techniques applied to wastes. The final version of the report, edited by the coordinator of the project: J. Rackham in August 2011, represents the completion of an important project of compilation, in a reference document, of the performances of NDA techniques dedicated to the characterization of special nuclear material in wastes, structured by container type and waste matrix type. The document has huge input of waste NDA systems performance values from Europe and USA. An extensive work was performed by the coordinator in structuring the project, collecting relevant data and drafting the report, which is now ready for a final publication in the ESARDA Bulletin, later in the year.

Modelling of NDA instruments:

Currently, the WG is further investigating the modelling results of the 3rd phase of the ESARDA Multiplicity Benchmark, consisting in assessing the performances of the Monte Carlo simulation of the response of a neutron multiplicity counter to californium sources and plutonium samples (results published in the ESARDA Bulletin issue n°42). The purpose of this investigation is to get a better knowledge of the various components of the modelling uncertainty. In 2011, a questionnaire was prepared and sent to the six participants in order to identify the sources of discrepancies between them and compare the most influent input data used (1) to model the counter, (2) to model the electronics, (3) to model the plutonium samples (included nuclear data). In parallel, a sensitivity study of the major sources of uncertainties affecting the Monte Carlo simulation of neutron multiplicity counters, pointed in the questionnaire, has been performed by P. Peerani. This study leads to an evaluation of the individual contributions to the uncertainty budget. The results of this study were presented to the WG in May 2011 and a paper was submitted. A new benchmark will be launched this year, asking the participants to run the same Monte Carlo input files, in order to finalize the analysis of the modelling uncertainty.

3. Future activities

In 2012, the WG will keep investigating the 2011 on-going projects and in addition, will address the following topics:

- The calibration of neutron counters without plutonium standards;
- Monte Carlo generation and validation of gamma spectra;
- Performance assessment of NDA instrumentation applied to the detection of illicit trafficking;
- NDA Needs for Euratom and IAEA Safeguards.

Technical sheet

Plutonium Assay by Controlled-Potential Coulometry

M. Holland

1. Objective of the Technique

Controlled-potential coulometry is a destructive analysis method that may be used for the quantitative determination of plutonium in samples taken from nuclear-grade product materials and reference materials in oxide, metal, and alloy forms and from nuclear-grade fuel cycle streams of plutonium nitrate solution. This instrumental method may be used for nuclear material accountancy and safeguards, and for material characterization and reference material certification. A measured mass of sample is dissolved and diluted; aliquots are taken by mass and chemically treated, and then subjected to electrochemical analysis. The electrochemical measurement determines the amount of plutonium in the aliquot. The assay or concentration result is calculated using the measured plutonium and the masses from the analytical sampling and dilution. For solid samples, the assay is typically reported as a percentage or mass content for solid sample, e.g. 88.04% Pu or 0.8804 g Pu / g sample. For liquid samples, the concentration is typically reported as a mass of plutonium per mass or volume of sample, e.g., 10.123 mg Pu / g sample or 10.567 mg Pu / mL sample. Solution density measurements are normally used to convert from a g/g-basis to a g/mL-basis.

2. Presentation of the Technique

2.1 Principle of Measurement

Sample aliquots are evaporated to dryness in sulfuric acid to remove volatile impurities and to generate a consistent and stable plutonium sulfate anhydrous salt. The dried plutonium salt is then dissolved in dilute mineral acid, typically sulfuric or nitric acid. The plutonium in solution is first reduced to Pu^{3+} at a stationary platinum or gold electrode maintained at a controlled-potential nominally 200 mV below the formal potential of plutonium. (If the mineral acid is nitric acid, then the working electrode is normally a gold electrode.) The reduction is continued for 5-10 minutes until the electrolysis current reaches a residual level, indicating completion of the sample reduction. The stationary electrode is then set to a potential that is nominally 200 mV above the formal potential of plutonium. The current that flows during the oxidation of the plutonium to Pu^{4+} is electronically integrated. The oxidation is continued for 5-10 minutes until the total coulombs of electricity generated from the reaction have been measured. The plutonium content is calculated from the coulombs of electricity using the Faraday's Constant to convert from coulombs to moles of plutonium. The relative atomic mass of the plutonium, obtained from mass spectrometry isotopic abundance measurements, is used to convert from moles to mass. The coulometer may be calibrated using electrical standards and Ohm's Law or using plutonium reference materials.

2.2 Procedure outline

- The dilute mineral acid that will be used to dissolve the dried plutonium aliquot is first subjected to the same electrochemical reduction and oxidation reaction sequence that will be used to measure the dissolved plutonium aliquot. This 'blank' measurement process ensures that the electrodes and the measurement cell are functioning properly. The 'blank' coulombs will be subtracted from the coulombs of electricity generated during the measurement of the dissolved plutonium aliquot.
- The plutonium is dissolved in the dilute mineral acid after the blank measurement is completed.
- The dissolved plutonium ions react at the polarized electrode and reduce until the Pu^{3+} ion is the dominant species and the potential of the Pu^{4+}/Pu^{3+} couple in solution matches the potential of the stationary electrode, at which time the electrolysis current is at a residual current level that is typically less than 10 µA.
- The timing circuit and the electrical integration circuit are set to zero, and the potential of the stationary electrode is then adjusted to the desired potential for plutonium oxidation.
- The plutonium reacts at the polarized electrode, oxidizing until the Pu^{4+} ion is the dominant species and the potential of the Pu^{4+}/Pu^{3+} couple in solution matches the potential of the stationary electrode, at which time the electrolysis current is at a residual current level that is typically less than 10 µA.
- The mass of plutonium measured during the oxidation of Pu^{3+} to Pu^{4+} is calculated from the quantity of electricity (coulombs) measured using the equation:

$$Pu = (Q_s - Q_b) \text{ x } C \text{ x } A_r / F f$$

Where: Q_s is the integrated current measured during sample oxidation, $\int i\,dt$

Q_b is the integrated current measured during blank oxidation

C is the calibration factor for the integration circuit

A_r is the relative atomic mass calculated from the plutonium isotopic abundance

F is the Faraday constant, 96,485.3399 Coulombs per mole

f is the fraction of the plutonium electrolyzed during the sample oxidation

- The assay or concentration is calculated by dividing the mass of plutonium measured by the mass of sample in the aliquot, based on the weight of sample taken and any subsequent dilutions during the preparation of the aliquot.

2.3 Chemical reactions

2.3.1 Reduction of plutonium at the stationary electrode, in preparation for measurement:

$$Pu^{4+} + e^- \xrightarrow{\text{Electrode}} Pu^{3+}$$

2.3.2 Oxidation of plutonium at the stationary electrode generates current from the flow of electrons, e⁻, which are integrated to measure coulombs:

$$Pu^{3+} \xrightarrow{\text{Electrode}} Pu^{4+} + e^-$$

2.4 Interferences

Several metal ions interfere: gold, iridium, palladium, platinum, iron, and neptunium. The four noble metals are not typically present in the nuclear-grade plutonium product materials or process streams. The extent of the interference from iron and neptunium depends upon the selection of supporting electrolyte, and also on the oxidation state of the neptunium.

Polymeric plutonium, if present, is not electro-active and will not be detected as plutonium. If present, Pu^{6+}, i.e., PuO_2^{+2}, may not be reduced during sample reduction, depending upon the selection of mineral acid used as the supporting electrolyte and the coulometric experimental parameters.

Organic contaminants that are not volatized during aliquot fuming can interfere by reacting at the electrode or by affecting the performance of the electrode. Hydrazine interferes and is not easily removed during routine sample pretreatment. Hydroxylamine is sometime present in process solution, but is removed when the aliquots are fumed to dryness several times in sulfuric acid.

The anions nitrate, nitrite, chloride and fluoride interfere, but are also removed during fuming in sulfuric acid. Nitrite anions in nitric acid supporting electrolyte are destroyed by adding sulfamic acid prior to measuring the blank.

Atmospheric oxygen interferes, especially in sulfuric acid, and must be removed prior to the blank and sample measurement by purging the supporting electrolyte and the atmosphere in the measurement cell above the solution with an inert gas.

The interference from iron can be eliminated by a mathematical correction when the iron content is known from another measurement, such as spectrophotometry or inductively coupled plasma mass spectrometry.

2.5 Sample size

The analytical sample must be representative of the bulk material from which it is taken. For plutonium oxide, metal, or alloy samples that are homogenous and stable, an analytical sample of 300-1000 mg that is taken with an uncertainty of ±0.05 mg, 1-sigma is typical and satisfactory. Following dissolution and dilution to obtain 3-5 mg Pu per gram of solution, aliquots containing 5-20 mg Pu are taken by mass, and fumed to dryness.

2.6 Apparatus

Instrumentation and equipment (figures 1 and 2) required for performing coulometric measurements:

- Analytical balances with a readability of 0.01 mg, in appropriate radiological containment.
- A potentiostat circuit that supplies the control-potential to the stationary (working) electrode.
- An integrator circuit that measures the coulombs of electricity produced from oxidizing the blank and sample.
- A digital voltmeter for measuring the control-potential supplied by the potentiostat and for electrical calibration.
- An instrument controller (computer), if automated operations is desired.
- A measurement cell composed of a glass container for the sample solution, a platinum or gold working electrode, a platinum counter electrode, a saturated calomel reference electrode, a stirrer, and an inert gas inlet, in appropriate radiological containment.
- A gas bubbler to saturate the compressed gas with water or the supporting electrolyte before introduction in the measurement cell, in appropriate radiological containment.
- Compressed gas cylinder and regulator system, high purity argon or nitrogen.
- Beakers, pipettes, and volumetric glassware for preparing reagents, typical laboratory equipment.
- Microwave oven or hot block for sample dissolution, in glovebox containment.
- Heat lamps or hot plate for aliquot fuming, in appropriate radiological containment.
- Conditioned power and uninterruptible power supply (UPS) are recommended.

Fig 1: Coulometer Instrumentation, Savannah River National Laboratory (SRNL) Coulometer

Fig 2: Cell Assembly, SRNL design, with modified PAR stirring motor

2.7 Accuracy and precision

Normal level: Results are accurate to 0.1% or better and the relative standard deviation is 0.1% or better. Measurement of aliquots containing less than 5 mg of plutonium will have greater uncertainty corresponding to the quantity of plutonium present. Alternative measurement methods such as isotope dilution mass spectrometry are recommended in preference to coulometric measurement below 5 mg of plutonium per aliquot.

2.8 International Target Values (ITV)

In nuclear safeguards measurements, the 2010 ITV for systematic (u(s)) and random (u(r)) variations for controlled potential coulometry are 0.1%. The 2010 ITV also specifies a target for the total uncertainty of 0.14% with coverage factor of 1.

2.9 Comparison with IDMS

Controlled-potential coulometry and isotope dilution mass spectrometry methods have similar levels of accuracy and precision for the determination of plutonium.

The setup cost for controlled-potential coulometry is less than IDMS; the latter is more expensive because a thermal ionization mass spectrometer (TIMS) is required for isotope ratio determinations. However, the capabilities and applicability of IDMS and the TIMS instrument are more extensive than that of a controlled-potential coulometer.

The cost for purchasing a coulometer station will range from $120,000-$200,000, (€80,000-€130,000) depending upon the instrument selected and the delivery requirements.

3. References

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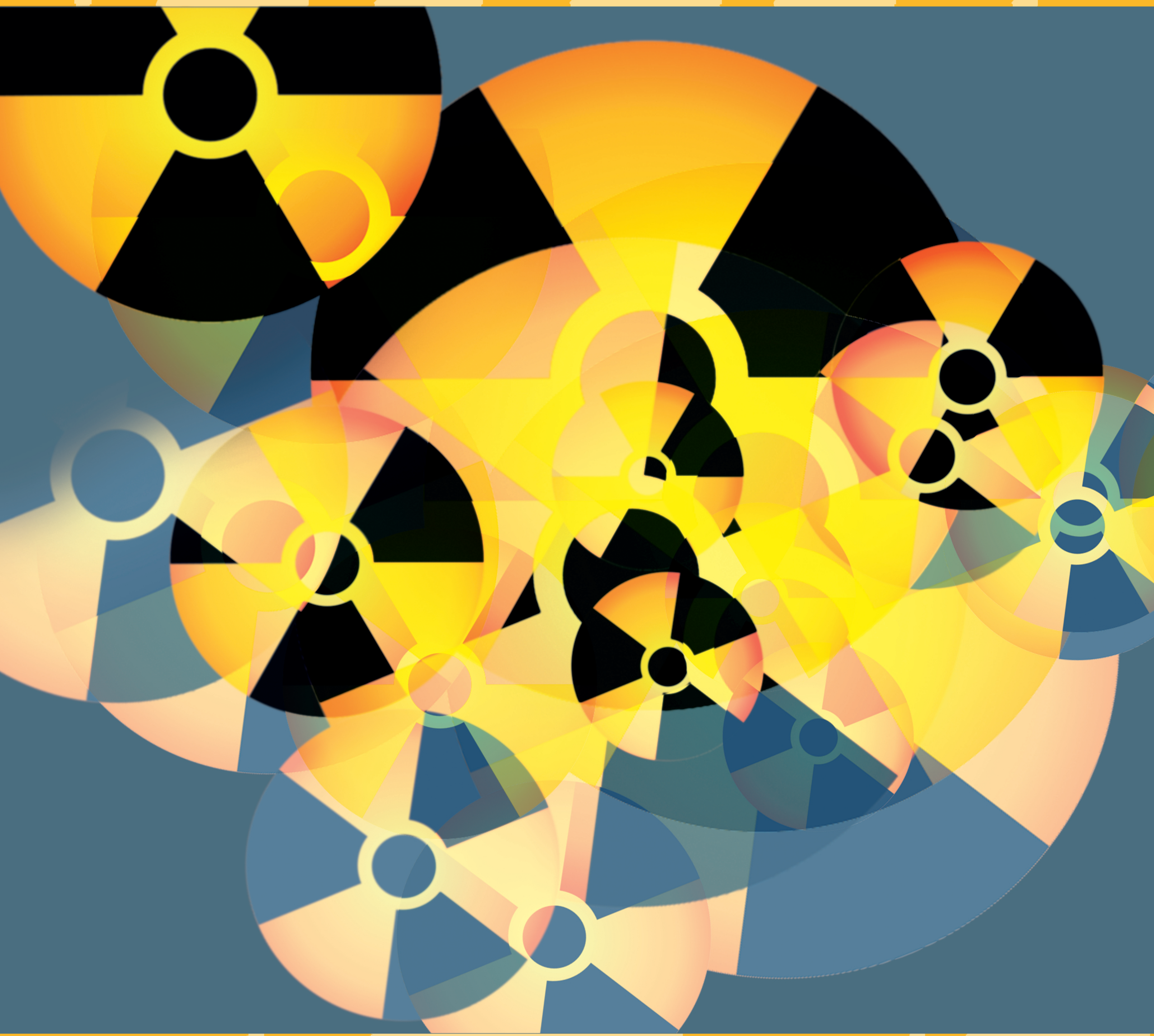

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