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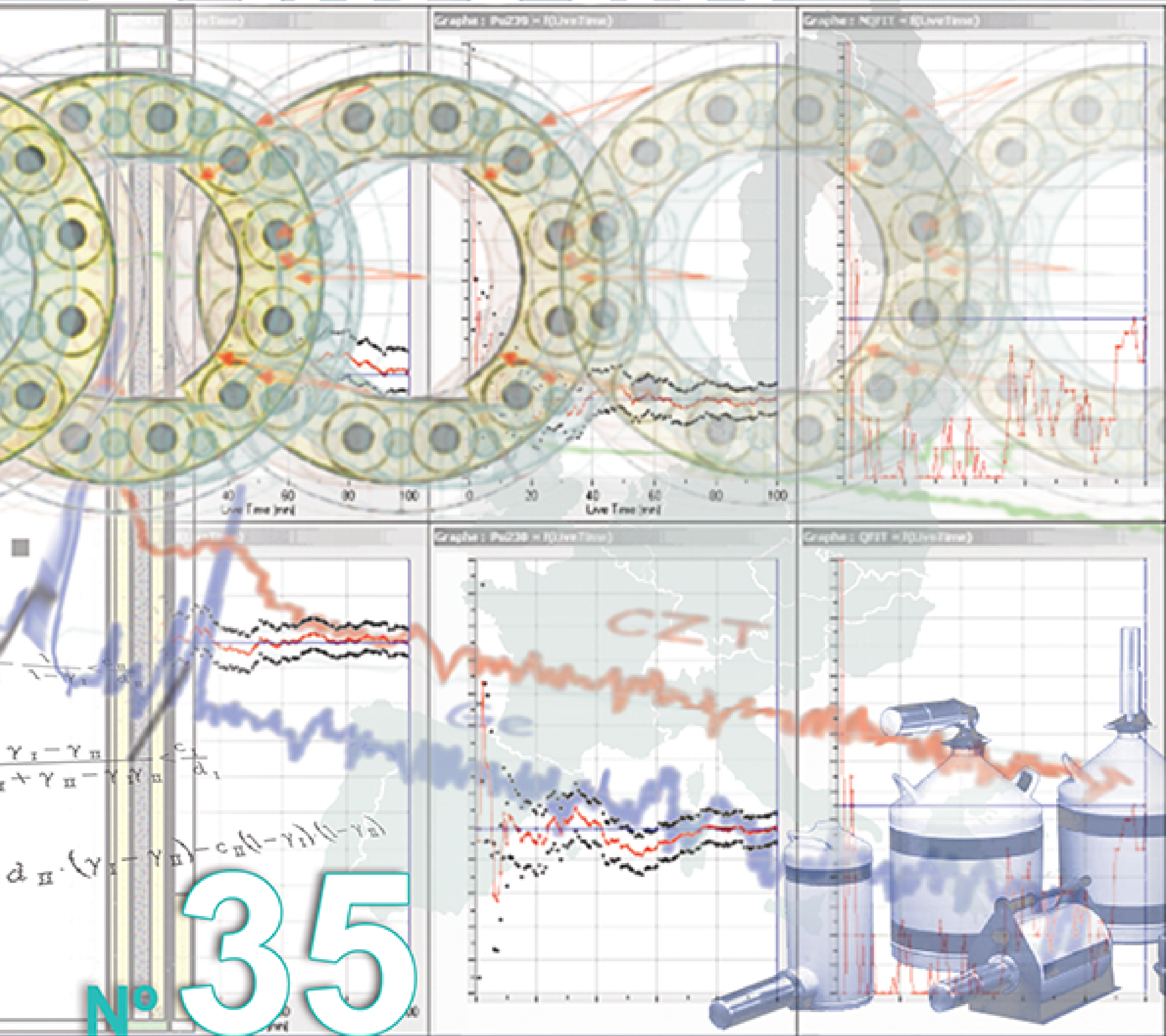

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Scientific and technical papers submitted for publication are reviewed by the Editorial Committee.

Manuscripts are to be sent to the Editor which, should strictly adhere to the “instructions for authors” available on the ESARDA website, page ‘Bulletin’. Photos or diagrams should be of a very high quality.

The accepted manuscripts will be published free of charge.

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ESARDA
European Safeguards Research and Development Association

Bulletin

Table of Content issue n° 35

Editorial

Presentation of Technical Sheets

With this issue n° 35, the ESARDA Bulletin opens a new section exclusively devoted to **Technical Sheets** (p. 52) or Worksheets.

Two years ago, the first Technical Sheets were posted on the website. Please visit the corresponding section at the following address:

http://esarda2.jrc.it/references/Technical_sheets/index.html

The Technical Sheets are part of the didactic approach set up by ESARDA in the field of Nuclear Material Accountancy and Control.

This approach consists of presenting a gradual didactic material on the website:
- The **glossary** that defines in a few words concepts, equipment, methods etc.
- The **Technical Sheets** that describe in a few pages the techniques used, their physical principle and their application fields;
- The ESARDA **course** that gives young professionals or students in nuclear engineering, the basics for understanding and using the safeguards concepts and technologies.

Technical sheets or worksheets are widely used in various fields of daily activities for teaching the basics of a technology:
- maintenance of cars
- cookery books or sheets
- DIY (do-it-yourself)
- instructions for / precautions of use (drug medicine, household electrical appliance)
- pedagogical: maths etc.

ESARDA will populate its website little-by-little with the worksheets regarding any given subject linked with safeguards and non proliferation. Where the subject fits with their field of interest, the Working Groups of ESARDA have indeed already drafted many of the Technical Sheets available on the website. In other cases, individuals have volunteered and dedicated fair amounts of time to draft them.

I invite you to explore the subjects covered by these Technical Sheets. If you detect anomalies, if you wish to debate their content, or propose subjects not covered by the current collection, your input will be most welcome.

I hope that you will read and use these Technical Sheets within your professional duties or your personal interest.

Scientific peer reviewed papers

AutoISO: a new acquisition and data review software for the use of isotopic composition analysis codes (MGA++, PC/FRAM and IGA)

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Abstract

In the framework of French domestic safeguards, inspectors from IRSN/DEND perform gamma spectrometric measurements to verify operator's declaration on uranium and plutonium. For this purpose, isotopic composition codes have been used for many years by the inspectors to measure uranium enrichment and plutonium isotopic composition. This paper presents new acquisition and data review software developed by IRSN/DEND that integrates automatically MGA++, PC/FRAM and IGA analysis (uranium and plutonium).

The feedback gained from isotopic composition measurements showed that the duration of the measurement to obtain a good gamma ray spectrum is a key factor for the accuracy of the result. The developer of the code provides a simple criterion to decide when to stop the acquisition, based on the total count in the spectrum with a recommended value greater than 10^6. This criterion is just a general indication and in many cases, it is not appropriate. For instance, the MGA++ analysis may be accurate with less count than 10^6. On the other hand, for spectra with high Compton scattering, it may be necessary to increase the total count in the spectrum.

Keeping in mind that the total count is directly related to the duration of the measurement, the main objective of AutoISO is to optimize the duration of the measurement as regard with results provided by isotopic composition code. The basic idea is to perform a cumulative acquisition, based on Gamma-Vision software from ORTEC and to perform periodically a isotopic composition analysis. AutoISO enables to perform this process completely automatically with the saving of all data. In order for the user to decide when to stop the process, a graphical view of isotopic composition results is available. Other features are available in AutoISO in order to ensure the quality of the data acquired, by looking graphically at information in the cumulative spectra: region of interest, total counts…

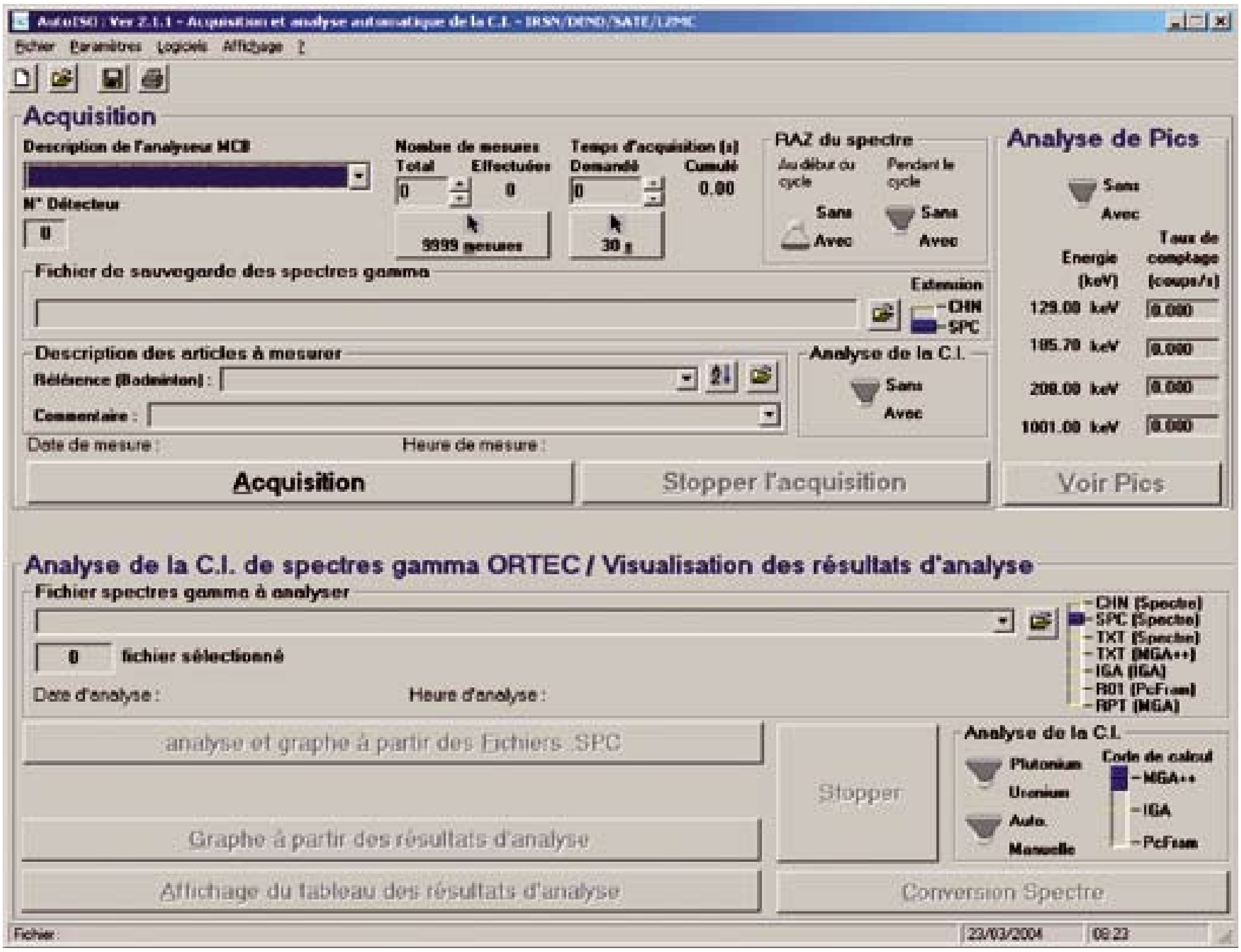
Since its development, AutoISO has been used intensively. It is not only a powerful tool to optimize acquisition duration (and subsequently to improve the quality of the measurements) but also an adequate software for the testing of the code performance. At that stage, only isotopic composition routines are integrated but it is intended to extent its capabilities for other codes like PLUM, FUNE which are dedicated to the measurement of plutonium mass in waste drum

Keywords: isotopic composition, MGA, MGA++, PC/Fram, IGA, PLUM, FUNE, uranium, plutonium

1. Introduction

In the framework of French domestic safeguards, measurements are performed by inspectors from IRSN/DEND to verify operator's declaration on uranium and plutonium. For this purpose, MGA++ [1] [2] has been used for many years by the inspectors to measure uranium enrichment and plutonium isotopic composition.

The feedback gained from direct MGA++ measurements showed that the duration of the measurement to obtain a good gamma ray spectrum is a key factor for the accuracy of the result (closeness of the agreement between the result of a measurement and a true value of the measurand) .The developer of the code provides a simple criterion to decide when to stop the acquisition, based on the total count in the spectrum with a recommended value greater than 10^6: for this value, counting's uncertainties become negligible compared to all other uncertainties [2]. This criterion is just a general indication and in many cases, it is not appropriate. For instance, the MGA++ analysis may be accurate with less count than 10^6. On the other hand, for spectra with high Compton scattering, it may be necessary to increase the total count in the spectrum.



Picture 1: main window of AutoISO

A software has been developed, AutoISO[1], to help user of an isotopic composition measurement code in deciding when to stop its acquisition: it does a cumulative acquisition, based on GammaVision software from ORTEC and perform periodically a isotopic composition analysis. AutoISO enables to perform this process completely automatically with the saving of all data. In order for the user to decide when to stop the process, graphical views of isotopic composition results are available. Other features are available in AutoISO in order to ensure the quality of the data acquired, by looking graphically at information in the cumulative spectra: region of interest, total counts…

The paper describes the main features of AutoISO and gives examples of applications. It concludes on some perspectives and other applications to extend its capabilities for other analysis codes.

1 It is based on a former software, AutoMGA++, which was dedicated to run MGA++ analysis. Since it includes now the capabilities to run PC/FRAM and IGA codes, it has been rename as AutoISO.

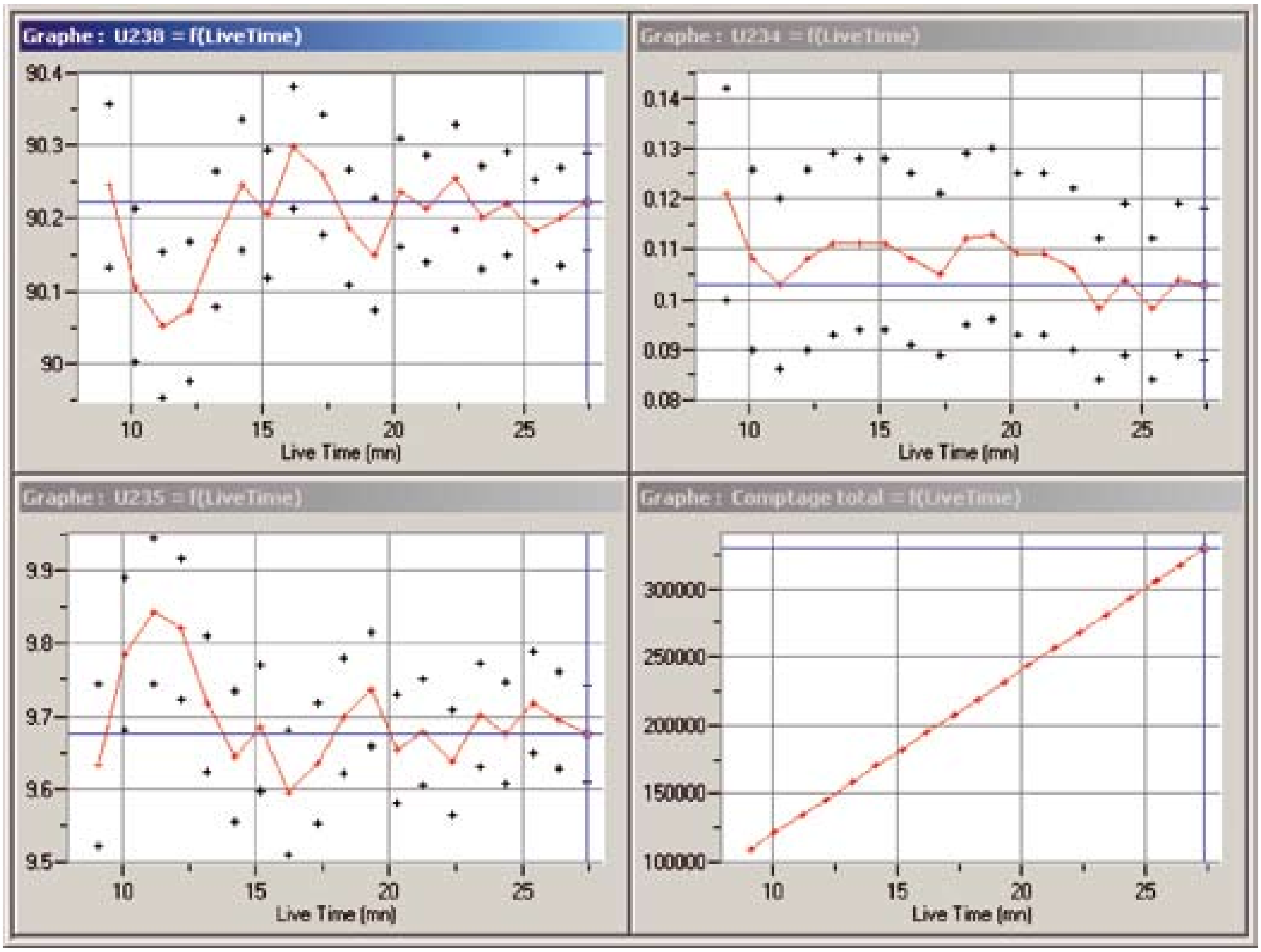
2. Main features of AutoISO

2.1 Description of equipment

AutoISO is running on a computer with Microsoft Windows system and has been tested with Windows 95, Windows NT4 and Windows 2000. Regarding the gamma spectrometric acquisition system, it is designed to work with an ORTEC system that uses a multi channel analyzer such as a DSPEC and GammaVision v 5.31 for the software. Regarding the MGA code, the MGA++ version 1.0.3, 1999 provided by ORTEC is used. SFRAM codes [3], a standalone version of PC/FRAM V4.2 [4] developed by Los Alamos National Laboratory as well as the code IGA 4.4.9 (Isotopie Gamma of Actinides) developed by the French CEA (DRT/DIMRI/SIAR) is used in AutoISO.

Picture 1 presents the main windows of AutoISO.

It is divided in two parts. The first one at the top is dedicated to the acquisition of spectra. The second one at the bottom concerns the data review.



Picture 2: example of a plot during the acquisition of a uranium sample. (Y-axis unit for each isotope: Mass %)

		Pic à 112.81 keV				Pic à 143.76 keV				Pic à 185.71 keV				Pic à 205.3 keV			
	Temps Acquisition	Surface Nette	Incertitude	Taux Net	Surface Brute	Surface Nette	Incertitude	Taux Net	Surface Brute	Surface Nette	Incertitude	Taux Net	Surface Brute	Surface Nette	Incertitude	Taux Net	Surface Brute
Indice	(s)	(Coups)	(Coups)	(Coups/s)	(Coups)	(Coups)	(Coups)	(Coups/s)	(Coups)	(Coups)	(Coups)	(Coups/s)	(Coups)	(Coups)	(Coups)	(Coups/s)	(Coups)
174	52200	288	132	0.01	6080	4818	212	0.09	12170	21317	225	0.41	26673	1650	153	0.03	5635
175	52500	278	133	0.01	6118	4862	213	0.09	12240	21448	225	0.41	26817	1660	154	0.03	5671
176	52800	307	133	0.01	6163	4891	213	0.09	12308	21571	226	0.41	26973	1673	154	0.03	5697
177	53100	307	134	0.01	6211	4912	214	0.09	12381	21717	226	0.41	27132	1677	154	0.03	5733
178	53400	303	134	0.01	6243	4942	215	0.09	12456	21862	227	0.41	27290	1689	155	0.03	5765
179	53700	299	135	0.01	6279	4974	215	0.09	12527	21970	228	0.41	27443	1706	155	0.03	5794
180	54000	298	135	0.01	6322	4995	216	0.09	12600	22081	228	0.41	27587	1718	155	0.03	5826
181	54300	297	135	0.01	6357	5034	216	0.09	12678	22198	229	0.41	27730	1719	156	0.03	5853
182	54600	280	136	0.01	6392	5076	217	0.09	12753	22332	229	0.41	27870	1730	156	0.03	5890
183	54900	283	136	0.01	6419	5121	218	0.09	12837	22446	230	0.41	28023	1732	157	0.03	5925
184	55200	298	136	0.01	6446	5132	218	0.09	12900	22554	231	0.41	28164	1746	157	0.03	5958
185	55500	304	137	0.01	6488	5166	219	0.09	12966	22675	231	0.41	28311	1746	158	0.03	5978
186	55689.3	312	137	0.01	6512	5168	219	0.09	12994	22728	232	0.41	28390	1752	158	0.03	5997
Moyenne	28049.40	149.08	91.04	0.01	3234.26	2585.84	146.76	0.09	6523.76	11449.57	154.46	0.41	14277.27	881.12	105.84	0.03	3025.34
Sigma	16150.3	89.8	32.1	0.0	1876.9	1535.3	50.7	0.0	3772.2	6590.6	54.8	0.0	8256.3	525.2	37.1	0.0	1757.4
Sigma %	57.6	60.2	35.3	31.3	58.0	59.4	34.5	8.3	57.8	57.6	35.5	1.6	57.8	59.6	35.0	23.7	58.1

Ok

Imprimer

Picture 3: example of region of interest analysis.

Picture 4: data review of already analyzed spectra.

Picture 5: data review of spectra to be analyzed.

2.2 Data Acquisition features

The user enters the total number of measurements he wants to run and the duration for each measurement. There is the possibility to reset or not the spectrum at the beginning of the first measurement and after each measurement. This may be used for two kinds of measurements: cumulative acquisition or repeatability testing.

The operator selects the calculation code among MGA++, IGA and PC/FRAM. At the end of each acquisition, a spectrum is saved (with an extension that is increased from 0001 to 9999) and, for instance, a MGA++ analysis is performed on the current spectrum. Then the next acquisition starts. During the acquisition, a plot of the results is performed (Picture 2) that shows the results as a function of the live time. This graphical tool includes all the previous results and it is possible to access to the complete MGA++ report by clicking from this plot to the point of interest. The user may decide to stop the acquisition whenever he considers that the result is adequate. This topic is discussed in the given examples in paragraph 3. At the end of the measurement, an interesting feature is the possibility to save all data in a single file, for future review.

Two ORTEC formats are available: ".spc" and ".chn" format. It is also possible for the user to remove the MGA++ analyses between each acquisition. Other acquisition features are available to control the quality of the measurement: analysis of four region of interest defined by the user for each acquired spectra (Picture 3) and the plotting of the total count as a function of the live time.

2.3 Data Review features

Analysis with AutoISO is completely flexible. It can be done during the acquisition or later on with the data review.

For instance, the next pictures present an acquisition of 112 cumulative spectra for a uranium sample.

- If MGA++ analysis is done, the results are stored in 112 text files (with *.txt extension). The review window (Picture 4) indicates the number of files, and the MGA++ version used for the analysis.

Clicking on the available button leads to pictures such as picture 2 : graphical views of the results; furthermore, a table can be exported directly in compatible excel data sheet with the complete data report of all analysis.

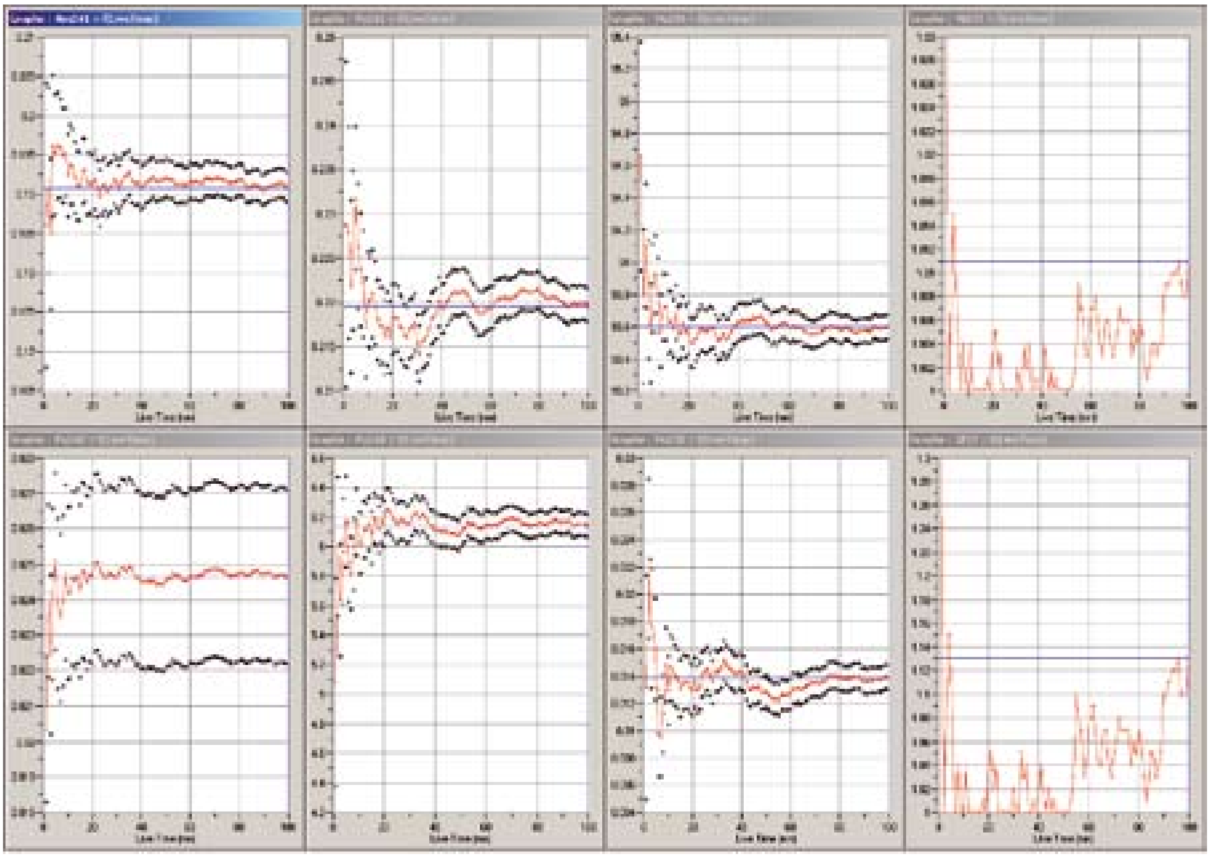
- If MGA++ analysis is not yet done, it is possible to recall the 112 *.spc files. The review window

			^{238}Pu (%)	^{239}Pu (%)	^{240}Pu (%)	^{241}Pu (%)	^{242}Pu (%)
Declared isotopic composition			**1.7E-2**	**93.7**	**6**	**2.3E-2**	**5.0E-2**
Life time (min)	QFIT	NQFIT	MGA++ Analysis				
90	1.1	1.009	1.37E-02	93.57	6.17	2.20E-01	2.48E-02
91	1.1	1.009	1.36E-02	93.58	6.16	2.20E-01	2.47E-02
92	1.11	1.009	1.37E-02	93.57	6.18	2.19E-01	2.48E-02
93	1.12	1.01	1.37E-02	93.58	6.17	2.20E-01	2.47E-02
94	1.12	1.01	1.37E-02	93.60	6.14	2.20E-01	2.46E-02
95	1.12	1.01	1.37E-02	93.60	6.14	2.20E-01	2.46E-02
96	1.13	1.011	1.38E-02	93.59	6.15	2.20E-01	2.47E-02
97	1.1	1.009	1.37E-02	93.59	6.15	2.20E-01	2.47E-02
98	1.1	1.008	1.39E-02	93.59	6.15	2.20E-01	2.47E-02
99	1.1	1.008	1.40E-02	93.59	6.15	2.20E-01	2.47E-02
100	1.13	1.011	1.39E-02	93.60	6.14	2.20E-01	2.46E-02

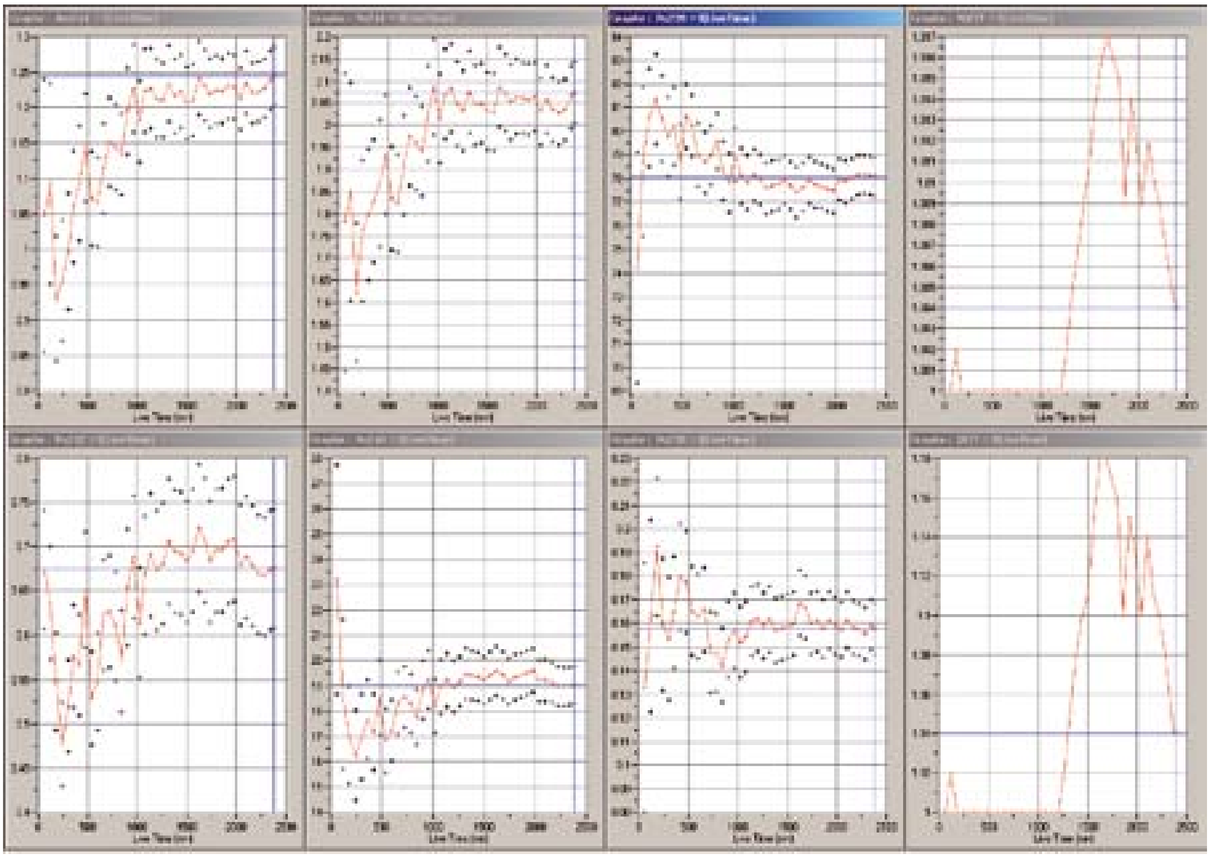
Table 1

			^{238}Pu (%)	^{239}Pu (%)	^{240}Pu (%)	^{241}Pu (%)	^{242}Pu (%)
Declared isotopic composition			**0.15**	**77.34**	**19.68**	**2.14**	**0.68**
Life time (min)	QFIT	NQFIT	MGA++ Analysis				
1800	1.16	1.015	0.161	77.7	19.4	2.07	0.70
1860	1.1	1.009	0.158	77.7	19.4	2.06	0.70
1920	1.15	1.014	0.161	77.6	19.5	2.06	0.71
1980	1.13	1.012	0.159	77.5	19.6	2.06	0.71
2040	1.1	1.009	0.157	77.9	19.2	2.03	0.68
2100	1.14	1.012	0.161	77.9	19.2	2.06	0.69
2160	1.11	1.01	0.158	78.0	19.1	2.03	0.68
2220	1.1	1.009	0.157	78.1	19.0	2.03	0.67
2280	1.08	1.007	0.156	78.2	19.0	2.03	0.67
2340	1.05	1.005	0.159	78.1	19.0	2.06	0.67

Table 2.



Picture 6: plutonium sample. (Y-axis unit for each isotope: Mass %)



Picture 7: plutonium in waste drum. (Y-axis unit for each isotope: Mass %)

(Picture 5) indicates now the number of files, and proposes to perform the MGA++ analysis with the plot of a picture such as picture 2.

3. Examples of applications

In this section, we present some different examples of acquisition and analysis with MGA++ for uranium and plutonium samples.

3.1 Plutonium sample

In this first example, acquisition and analysis are done every minute with a total number of a hundred acquisitions.

Table 1 gives the isotopic reference value of the plutonium sample and the last ten results given by MGA++ analysis.

Results are very stable over time. This can be seen on the next picture (Picture 6) that presents the overall results for the hundred measurements with uncertainties' values. This plot summarizes all results for the different plutonium isotopes (238 to 242), and for ^{241}Am. It also gives the values of the two indicators QFIT and NQFIT. They are quality indicators on how good was the deconvolution of the gamma rays of the spectrum. QFIT is the reduced chi-squared, NQFIT is the intensity-normalized of the reduced chi-squared as defined in [2] and [5]. They should be close to 1. From this plot, it can be seen that the results' convergence is obtained after 40 minutes.

3.2 Plutonium in waste drum

The next plutonium example is the measurement of plutonium in a waste drum. Table 2 gives the isotopic reference value of the plutonium sample and the last ten results given by MGA++ analysis.

The convergence of the results is quite long to obtain, probably after 1000 minutes. This can be seen on the next picture (Picture 7) that presents the overall results for the forty measurements with uncertainties' values. The experimental conditions were the following: a plutonium mass around 120 mg in a 118-liter drum whose density was equal to 0.14 g/cm^3, with the presence within the drum of highly active ^{137}Cs sources. This explains this long acquisition because of the very poor signal to noise ratio within total absorption peaks due to Compton scattering effect: the number of counts in the 208 keV peak due to the photoelectric effect is approximately twice less significant than that number of counts due to Compton scattering. For this measurement, the 10^6 counts are obtained at the 3rd acquisition point in the plot whereas the convergence of the result is not reached yet.

3.3 Uranium samples

This section presents results obtained with different uranium enrichment from natural enrichment to highly enriched uranium.

Sample number	^{235}U	^{238}U	Comments
1	0.71	99.28	Uranium in a waste drum
2	5.10	94.90	Small uranium sample
3	9.60	90.40	Small uranium sample
4	9.60	90.40	The number (3) uranium sample is embedded in a vinyl matrix within a waste drum
5	92.70	7.3	Small uranium sample

Table 3

Picture 8 presents results obtained for the measurement of ^{235}U for all samples.

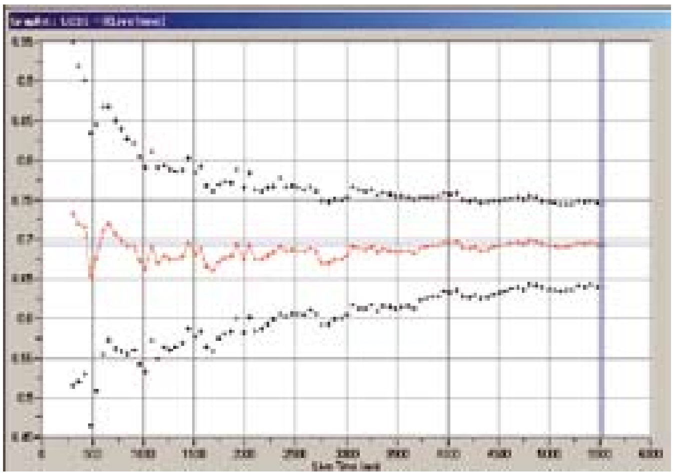
Except for sample 4, the measured values are close to the reference value. The examples of samples 2, 3, and 4 show the interest to follow the evolution of the results with time in order to decide when to stop the acquisition.

The example of sample 4 is quite different. For this measurement, sample 3 has been put with a drum that contains a vinyl matrix. The duration of the acquisition in order to obtain the convergence of the result is quite long (around 400 minutes). Furthermore, the result is biased, with a value of 8.3 % instead of 9.6 %. The reason is clearly the effect of the gamma ray absorption of the matrix: the signal to noise ratio is reduced mainly due to Compton scattering.

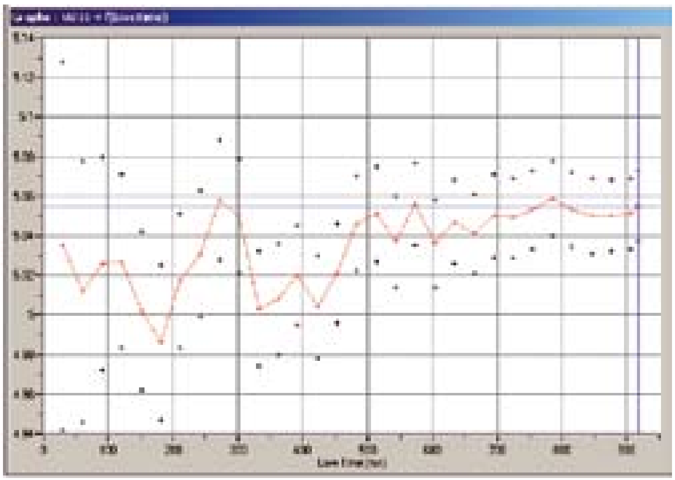
Another comment from these pictures concerns the uncertainties given by MGA++ analysis. They are clearly underestimated for sample 2, 3, 4, and 5 when the convergence is not yet obtained. This result is quite general regarding our experience feedback. Some source of uncertainties are not taken into account with MGA++.

The given examples show the necessity for an operator to decide properly when to stop the acquisition. The first step is the AutoISO capability to show the evolution of the result with time. At least data are available for the operator to make his decision!

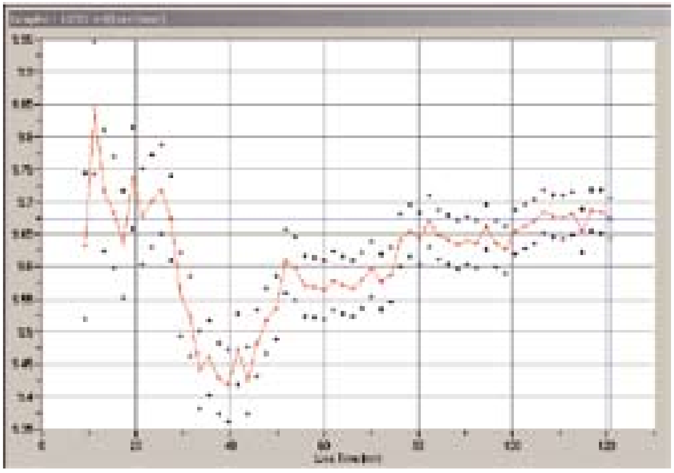
However, this decision must be, as much as possible, "user independent". To reduce the operator's influence on the isotopic composition final results, internal benchmarks have been performed on several samples and several configurations, without the knowledge of the true value for the operator at the



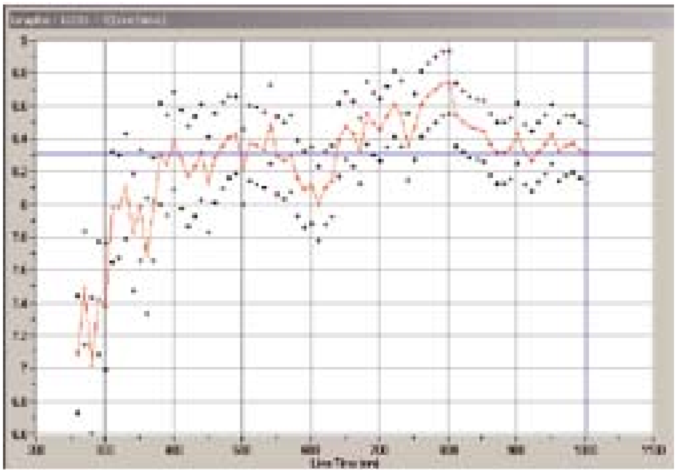
(Sample 1). Reference value for 235U: 0.71 %



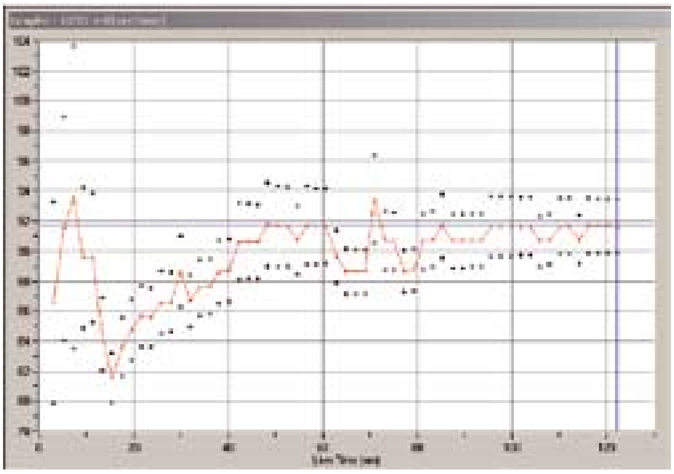
(Sample 2). Reference value for 235U: 5.1 %



(sample 3). Reference value for 235U: 9.7 %



(Sample 4). Same as 3 but within a vinyl matrix



(Sample 5). Reference value for 235U: 92.7 %

Picture 8: different results for uranium sample. (Unit Y-axis for each isotope : Mass %)

time of the measurement. From these benchmarks, general feedback on how the operator made his decision to stop the acquisition was obtained and rules have been proposed.

The second step is the setting of a global and automatic rule that will be user independent. This work has started, and some rules have already been implemented in the software. They need to be tested to validate their robustness. However, we still think that the operator should have the "last world", taking into account its expertise as a key factor to have good measurement.

4. Conclusion, other applications and perspectives.

Inspectors have used AutoISO for field measurements with an excellent feedback. Despite its simplicity, it has been a significant improvement for the quality of the measurement. Indeed, it is an efficient way to reduce the operator's influence on the final result since this results depends mainly from the decision to stop or to continue the acquisition of the spectrum. An interesting feature for AutoISO would now be to include an automatic analysis of the evolution plot in order to calculate automatically when to stop the acquisition: this will leads to an optimized acquisition duration with the best uncertainty.

Users have suggested other applications; some of them already available. For instance, it is possible to use the data review features of AutoISO to analyze results from MGA code (version distributed by CANBERRA). It would be interested to be able to perform directly the analysis with AutoISO, but it is necessary for that to have a MGA version that can be run from a command line, without the window interface. Analysis of other codes will be integrated in AutoISO like PLUM and FUNE [6], which are dedicated to the measurement of plutonium mass in waste drum.

Furthermore, AutoISO is used for the validation of gamma spectrometric analysis tool in various configurations. It is very useful to conduct repeatability studies and experimental design in order to determine influencing factors.

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Performance Evaluation of Verification Regimes

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Abstract

We develop a framework for evaluating the performance of monitoring and verification regimes. Verification of compliance is described as a binary random variable We show that there is no fundamental dif-ference between verification and confidence-building measures. Some ideas are presented on how to develop objective measures for assessing the significance of monitoring under less than robust inter-national verification regimes. Using a game-theoretic approach for the analysis of a universe con- sisting only of two States, we show that it would not be possible to reach a desirable equilibrium in the operation of treaties with less than robust verification regimes.

Keywords: Verification models; synergies; confidence-building measures; non-cooperative two-person games; Nash equilibria; integrated safeguards.

1. Introduction

Verification of compliance is perhaps the most crucial and controversial issue in arms control treaties. States may not ratify a treaty if they conclude that it is "unverifiable", or, more generally, contrary to their "national interest". Leaving aside the political dimensions of the arguments, is it possible to treat the verification issue in a relatively objective manner, namely, in the context of specifying treaty goals and measuring the extent to which they can be or have been reached? Objectivity implies the existence of a universally acceptable reference system for developing treaty models and analyzing their performance. Some work has already been done towards that goal [1]-[4]. Questions have been raised about the feasibility of attaining some of the stated goals, the sufficiency of the information provided by the monitoring systems specified in each of the treaties and the treatment of the term "compliance" as a dterministic variable. In a case study under the auspices of Pugwash and the Stockholm International Peace Research Institute (SIPRI) it has been concluded that the verification regime of the Chemical Weapons Convention (CWC) cannot detect the diversion of dual use chemicals from legitimate uses [5].

Some obligations undertaken by the States are so broad and ambiguous that no objective measure could be specified and applied. In the Non-Proliferation Treaty (NPT), States agree to "…not in any way assist, encourage or induce other States to acquire nuclear weapons". In the Treaty on Conventional Forces in Europe (CFE), the signatories seek to "achieve greater stability and security in Europe". The CWC requires that States "not assist, encourage or induce in any way anyone to engage in any activity prohibited by the manufacture of chemical weapons". Adherents to the Comprehensive Nuclear Test-Ban Treaty (CTBT) are obligated to "refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapon test explosion or any other nuclear explosion". The use of such ambiguous terminology may be appropriate in political discourse in which the ensuing arguments are resolved through compromise leading to consensus. However, compromise is not an option in arms control treaties that specify verification of compliance. It is expected that the decision-making mechanism will generate an answer as to whether or not a State complies with a treaty. For ambiguous obligations, definitive decisions are not possible. For example, under a verification regime, the term "greater stability" has no meaning. To require verification of compliance with the goal of achieving "greater stability" one would need to define more than one stable equilibrium state and rank them in accordance with their significance. Similarly, verifying compliance with the obligation "not to assist… in any way anyone…" is an open-ended obligation that would require an open-ended monitoring system. Even under the assumption that compliance could be defined, the information that would need to be collected by such a system would be difficult, if not impossible, to specify *a priori.*

Given the problems associated with verifying compliance with ambiguous obligations, one option would be not to rely on existing treaties, or not to ratify new ones, that include such obligations. However, there is a broad consensus that the primary goals of the various arms control treaties are beneficial and desirable. What causes disagreements about the treaties is the extent to which these goals can be attained. In other words, problems arise in the implementation of the treaties, namely, in the design of feasible verification systems. If a monitoring regime were to provide a high degree of assurance that the signatories to a treaty would abide by their obligations, then such a treaty could become an essential component of national security strategy. The benefits would be worth the costs associated with the operation of the treaty. On the other hand, if confidence in the verification regime were low, the costs of implementing the treaty would not be justified in terms of their contribution to the national security strategy. It is clear that the level of confidence could range from zero to almost one hundred percent. Given the nature of the treaties, and the fact that measurements involve uncertainty, perfect monitoring is impossible. Thus, the confidence level may be anywhere between the two extremes depending on the ability of the monitoring system to collect and analyze relevant data. One then is faced with the task of assessing the impact of imperfect monitoring on verifying compliance. Two major factors affect the performance of a monitoring system. One pertains to the presence of ambiguous treaty obligations or goals. Although it would be difficult, if not impossible to design a system to monitor for compliance with such obligations, the concepts of fuzzy logic could prove useful [1], [3]. Even if the obligations in a treaty are clearly defined and measurable, the verification regime specified in the treaty may be insufficient as in the case of thiodiglycol in the context of the CWC. In this paper we extend our previous work and propose a classification scheme for verification regimes. To illustrate the underlying concepts and evaluate the impact of the various classes of verification regimes on the operation of a treaty, we assume that the universe consists of two States and the problem is modeled as a non-cooperative two-person game.

In the first part of the paper we discuss a scheme for classifying verification regimes ranging from those characterized by the absence of any type of monitoring to those requiring the collection of all necessary and sufficient information needed to verify a desirable level of compliance. Ratification of the treaty implies that each State relies on the obligations undertaken by the other State in the formulation of its national security strategy. The issue is modeled as a two-player game in which the desirable outcome, namely treaty compliance by both States, is an equilibrium condition. The impact of various classes of verification regimes on the search for equilibrium is examined. For a universe consisting of more than two States, the same reasoning would apply, but the mathematical formulation would be much more complicated.

2. Classes of verification regimes

The term *verification* assumed a prominent role with the CWC and the CTBT in which separate sections of the treaty text are devoted to the description of verification regimes. In previous treaties, the term was either absent *e.g.,* in the Geneva Protocol or, as in the case of the NPT, mentioned in some broader context, such as, a State "undertakes to accept safeguards,…, for the exclusive purpose of verification…". Nevertheless, the latter´s model verification agreement INFCIRC/153 set out a clear framework. Following the trend set by the CWC and the CTBT, extensive discussions have been taking place in the Committee on Disarmament for specifying a verification regime for the Biological Weapons Convention (BWC). These discussions have yet to produce any results, because it is becoming apparent that if an acceptable regime could be specified, it would, very likely, be complex, intrusive, expensive and costly. With a heightened concern about proliferation of "weapons of mass destruction", return to a regime without some type of monitoring, evaluation and assessment is very unlikely. Given that the goals of the BWC are considered desirable, the question is how does one evaluate the impact of imperfect verification on the operation of the treaty.

In treaties incorporating verification regimes it is expected that the monitoring system would provide information to ascertain the "truth" about compliance. In the political arena, verification is typically interpreted to imply a yes/no answer. That is a gross oversimplification. As with any decision based on measurements, a more appropriate answer would be probable yes or probable no. However, even such a probabilistic outcome is not as simple as it might appear. A probable yes or probable no requires the *a priori* establishment of a decision threshold. Depending on the value of the threshold, a State might or might not be in compliance. The establishment of a decision threshold also involves uncertainty. Consider the case of key precursors in the CWC. The States Parties submit quantitative declarations and the Organization for the Prohibition of Chemical Weapons (OPCW) verifies their accuracy. In the SIPRI study, it was shown that in a manufacturing process, a necessary condition for detecting diversion is the definition of a life-cycle for the product. Leaving aside the issue of diversion and concentrating only on the verification of the declared information, even the verification of the declarations involve uncertainty. Depending on the intrusiveness and thoroughness of the accounting mechanism the inevitable discrepancies may range from small to large. Where does one set the threshold for non-compliance? At 1, 5, 10, or 50%? A similar question may arise with the CTBT. As the magnitude of detected seismic events decreases, the uncertainty in discriminating between underground nuclear explosions and other seismic events increases with a corresponding decrease in the probability of detecting low level nuclear explosions. One can find similar examples in other treaties with specified verification regimes. For any detection threshold, the subsequent yes/no decision has a corresponding impact on the national security of the States. It is easy to see that following this line of reasoning, a host of other questions arise which are beyond the scope of this paper. If the requirement for a binary decision is removed from the verification regime, compliance may be measured as the probability not to detect any irregularity, if in fact none exists. Thus, for any given verification regime, *veritas* has many faces.

If the problems associated with implementing a verification regime for a particular treaty become insurmountable, the alternative regime of "confidence building measures" is introduced. Such a regime implies that States intend to abide by their obligations under a treaty without being held accountable to a, presumably, higher standard of behavior implied by the obligation to comply with the terms of a treaty. The information collected through monitoring is considered sufficient to inspire confidence that they are fulfilling their obligations, but insufficient to provide proof. The data collected using such a concept, whether by declarations, sensing, inspections, or some combination of these monitoring tools, are not considered sufficient to lead to definitive conclusions about compliance. Thus, uncertainty is the central element of both regimes, the only difference being that in confidence building measures the uncertainty is explicitly accepted while in verification of compliance there is a pretence that uncertainties do not exist. Having argued that even under a verification regime, definitive conclusions about compliance are not possible, we can conclude that confidence building measures and verification are identical concepts.

2.1 Verification regimes

We define a *verification regime* as a decision-making system designed to ascertain whether and to what extent a State fulfills its obligations under a treaty. The system is *static* if the decision is taken at a single instance and does not depend on prior decisions. If, on the other hand, the decision at a given time is conditioned on preceding decisions, the system is *dynamic* and is subject to Bayesian analysis. This paper considers only the static case. In addition, we assume that the verification regime is called upon to make decisions on only those obligations which are unambiguous and measurable. The case of un-measurable obligations is beyond the scope of this paper.

The decision-making mechanisms could be classified into three major categories: *centralized*, *collective* and *decentralized*. A fourth category is that of *no verification*, designating the absence of any decision-making mechanism associated with a given treaty. Although these terms are not used explicitly in the treaties, the categories can be viewed as idealized versions of existing verification regimes. Under a centralized verification regime, an independent international organization makes the decision about compliance using information collected by the organization. The International Atomic Energy Agency (IAEA) is the closest example of such a regime, although the word compliance is not used explicitly in the NPT. Nevertheless, seeking to account for all the material within the nuclear fuel cycle is akin to monitoring for compliance. The calculation of Material Unaccounted For (MUF) and its use as a decision criterion illustrates the above mentioned measurement of compliance in reference to the nuclear fuel cycle. Under collective verification, monitoring is done by an international authority and the assessment of the collected information is left to a decision-making body consisting of the States parties to a treaty. The texts of the CWC and the CTBT imply such a structure. The CWC requires the States Parties to "…establish the Organization for the Prohibition of Chemical Weapons to achieve the object and purpose of this Convention, to ensure the implementation of its provisions, including those for international verification of compliance…" [CWC, Article VIII]. Similarly, in the CTBT "The States Parties hereby establish the Comprehensive Nuclear Test-Ban Treaty Organization…to ensure implementation of its provisions, including for international verification of compliance with it…" [CTBT, Article II]. In a decentralized verification regime, there is no international authority that collects processes and evaluates information to ascertain compliance. Instead, the information is collected and used by each of the member States. An example of such a regime it the CFE treaty. Information is provided by each State to other States, or is collected by inspectors from member States during inspection visits. Each State may make its own independent assessment of the available information. The Organisation for Cooperation and Securityin Europe (OSCE) Communications System is no more than an infrastructure for transporting data. It has no monitoring function. Finally, the Geneva Protocol is a good example of a treaty belonging to the category of no verification.

2.2 Monitoring systems

The decisions of the verification system are made solely on the basis of data collected by a *monitoring system* comprising one or more measurement components. The data used to evaluate compliance may be generated by instruments placed in various locations, collected by inspectors, provided by the States in some form of declaration, or extracted from sources in the public domain. The information provided by the inspectors may consist of data generated by instruments that are operated by the inspectors, observations made by them, and data retrieved from databases, electronic or other. In some treaties, the term *Technical Secretariat* is commonly used to refer to the operator of the monitoring system in order to differentiate between the decision-making function and those of collection, processing and analysis. In a decentralized verification regime it is conceivable to operate a monitoring system without a Technical Secretariat. Even though each State collects the information on its own through cooperative arrangements with the other States, the data may still be collected using instruments, inspectors or a combination of the two. The only difference is that they are under the control of the State rather that the Technical Secretariat. Treaties with no provision for verification have, by definition, no monitoring systems. Close examination of the various measurement components reveals that, for the decision-making function, there is no substantive difference between that data generated by unattended instruments and those operated by inspectors if both categories of instruments are under the control of the Technical Secretariat. Although different factors affect the reliability of the data generated by instruments in each of the two categories, from a decision-making perspective, the sole significant factor is that the source of the data is under the control of the decision-maker. Similarly, the information provided to the Technical Secretariat by a State is in the same category as that retrieved by inspectors from databases that are under the control of the States. In both cases, the issues pertaining to the value of the information are similar, because the sources of data are not under the control of the Technical Secretariat. Conversely, the information collected by inspectors through observations is in a category by itself, because the data collection mechanism, namely, the inspector, is under the control of the Technical Secretariat. Nevertheless, the reliability of the data is affected by factors that are different from those affecting the reliability of the data collected by instruments, for obvious reasons. For equally obvious reasons, from the point of view of the decision-maker, completely different factors affect the reliability of public domain data collected by the monitoring system.

The preceding discussion is summarized in Table 1. The verification regime of a given treaty may consist of one or more of the possible combinations indicated in the table.

3. Implications for verification of compliance

The objective of verification is to ascertain the extent to which a State complies with the terms of a treaty. Another way of stating it is to calculate the probability of compliance or non-compliance using the data provided by the monitoring system. Thus, the probability of detection is conditioned on the information content of the data. In the present context, the term “information” is used in the information-theoretic sense. If the information content of the data were perfect, the probability of detecting compliance would be one. In reality, only imperfect information is available, making the probability less than one. To compute the probability of detection, it is necessary for the data to possess quantifiable attributes, such as validity, sufficiency, integrity and timeliness. For the purposes of this paper we specify the meaning of these terms as follows:

Validity refers to the relevance of the data to the verification objective. If a bit of information has a significant impact on the decision-making mechanism, then its corresponding measure of validity is high and vice versa. For example, if in a given set of data elements only half contain useful information regarding compliance, the validity of the set would be 0.5. Ideally, the only type of data used in the detection of compliance would be valid data. In reality, the total amount of data being processed is a combination of valid and extraneous data. The implication of using data with low validity is that the benefit derived from such a type of data might be

Table 1. Possible combinations of verification regimes and monitoring systems

Monitoring System	Verification Regime			
	Centralized	Collective	Decentralized	No verification
Instruments (Technical Secretariat)	Yes	Yes	No	No
Instruments (States)	Yes	Yes	Yes	No
Inspectors (Technical Secretariat)	Yes	Yes	No	No
Inspectors (States)	Yes	Yes	Yes	No
Declarations (States)	Yes	Yes	Yes	No
Public domain	Yes	Yes	Yes	Yes
Absent	No	No	No	No

low compared to the cost of collection and processing. Another term that could be used to describe this concept is relevance. Given that a unit of data has a measure of validity, one also needs to consider whether it contains all the necessary information for detecting compliance.

Sufficiency refers to the amount of information necessary for making a decision with a desired degree of confidence. If, for example, the decision-making mechanism requires 100 valid data elements, but only 70 are available, the sufficiency would be 0.7. To increase the probability of detection one would need to increase the sufficiency of the valid data to as close to one as possible. Given that valid data are generated by the monitoring system, one could develop a relationship between a desired sufficiency and the complexity of the monitoring system.

Integrity measures the relationship between the data generated by a source, typically a sensor, and the data used in making a decision and attributable to that source. Under ideal conditions, a data unit entering the decision-making mechanism would be identical to that generated by a source having integrity of one. In practice, the probability is less than one that any data unit would enter the decision-making mechanism uncorrupted. Thus, the integrity of a data unit could have any value between zero and one. Data may be corrupted by external disturbances. They could be caused by natural phenomena or through human intervention. The intervention could be unintentional or intentional. Integrity, as defined in this paper, covers all categories, the difference between them being only in the assignment of the respective probabilities. The effect of natural causes on transmitted and processed data has been studied extensively under a variety of environmental conditions and models have been developed. On the other hand, there is little quantitative information available about the effects of human intervention, less so about intentional human intervention. The latter category is primarily addressed under the topic of "security" with emphasis on identifying "threats" and developing defensive procedures against them. Little, if any work has been done in the development of quantitative models for characterizing this class of disturbances.

Timeliness describes the relationship between the instant a source generates a bit of information and the instant when the decision-maker needs that piece of information. It measures the probability with which the data will arrive at the decision-maker within a specified time window from the instant they were generated by the source. A probability of one indicates that the transmission delay between the source and the user of the data is less than or equal to the specified time window. Thus, timeliness depends on two variables, width of the time window and transmission delay. If the time window becomes very wide and the transmission delay very small, it is possible for timeliness to assume the value of one. On the other hand, if the specified time window were very small, a threshold might be reached beyond which the transmission delay could not be reduced to a value that would give a timeliness of one. Unless one is concerned with delays in the order of fractions of a second, propagation delay depends on the design of the monitoring system, while the specification of the width of the time window depends on the performance specifications of the decision-maker.

The attributes of the data used in detecting compliance can easily be translated into attributes of the components of the monitoring system, declarations, inspectors, instruments, and public domain. Table 2 shows which of the four attributes are measurable for each of these components. It should be noted that in the integrity of the data collected by inspectors through personal observations might not be

Table 2. Relationship between monitoring system components and data attributes

Monitoring System Components	Attributes			
	Integrity	Timeliness	Sufficiency	Validity
Declarations	Not measurable	Measurable	Measurable	Measurable
Inspectors	Not measurable	Measurable	Measurable	Measurable
Instruments	Measurable	Measurable	Measurable	Measurable
Public domain	Not measurable	Not measurable	Measurable	Not measurable

easily quantifiable. Intuition, observation, reasoning are human characteristics not easily measurable. Although these attributes might not be measurable, they play an important role as qualitative inputs in a verification regime. The integrity of the data contained in the declarations cannot be quantified because the source would be outside the control of the monitoring authority.

Using these categories one can construct various models of monitoring and verification regimes and analyze their performance. To calculate the detection probability for compliance it is necessary, first, to calculate the probability that all necessary information for detecting compliance is available decreases very rapidly. For example, given values of 0.95, 0.9, 0.85, 0.8 for timeliness, integrity, validity and sufficiency, respectively, and given the independence of these attributes which may be questioned, the corresponding probability of availability of the necessary information is 0.58.

To illustrate how the proposed modeling approach could be used, we examine how two States would behave under various monitoring and verification scenarios. For simplicity we define three classes of verification regimes, robust verification, no verification, and reactive verification. A robust verification regime occupies one end of the spectrum, involves the collection of all necessary information for evaluating compliance regardless of cost and includes consequences in case of non-compliance. Such a regime may be called a *proactive* regime, because an international authority initiates the collection and evaluation of information and draws conclusions about compliance. Under a regime of no verification, there is no international body to assess compliance. The intermediate stage of reactive verification involves an international authority, such as a technical secretariat, that reacts to information it receives and draws conclusions about compliance. Such a regime also includes consequences. A crucial difference between a proactive and a reactive regime is that the data collected by a proactive regime are designed to maximize verification of compliance, while the data received by a reactive regime may be incomplete, random, invalid, or conditioned to generate false conclusions regarding compliance.

4. Application to a two-state universe

Let the universe of a treaty consist of two States, I and II, which agree not to produce nor to acquire specified weapons. In all three cases it is assumed that the States, regardless of their obligations under the treaty, consider the alternatives of complying or not complying with the treaty. Three different possibilities are taken into consideration by the two States: no verification, reactive verification and proactive verification. In a proactive verification regime, such as the IAEA safeguards system, if a State violates the treaty, the international authority would detect the violation on the basis of data provided by the monitoring system. In a reactive regime, such as the Standing Consultative Committee for SALT, the international authority might detect the violation either accidentally or from information provided by the other State, or it might not detect the violation at all. For the sake of simplicity it is assumed that in the second and third case false allegations are not possible.

In order to evaluate the usefulness of these three possibilities, we assume that both states consider - despite the treaty - the alternatives to comply or not to comply with the provisions, C or NC, and we assume furthermore, that the Nash equilibria, see e.g. Myerson [6], of these strategic games do predict the actual behavior of the two states appropriately, in other words, we interpret the equilibria in a *normative* sense. This type of information would be useful to those who would be negotiating an arms control treaty and to those who would be interested in evaluating the effectiveness of an existing treaty.

It should be mentioned that analyses of this kind have been performed already for a long time in various contexts. Rapoport [7] and Maschler [8] were probably the first ones to study so-called Inspector Evader games, and Brams and Kilgour [9] explicitly considered verification games. The symmetrical models developed subsequently have not yet been published before, as we assume.

4.1 First Model: Absence of verification regime

The *normal form* of the non-cooperative two-person game describing the first possibility mentioned before is represented graphically in Figure 1.

The payoffs to player I and player II are given in the lower left and upper right corners of the boxes, respectively, which represent the possible strategy combinations. The zero payoffs in case of treaty compliance by both players are simply normalizations; furthermore, we assume

$$0 < c_I < d_I \text{ and } 0 < c_{II} < d_{II}\,. \qquad (1)$$

These inequalities are based on the assumption that, if one State has weapons, the other State is at a greater disadvantage if it does not have any rather than if it does.

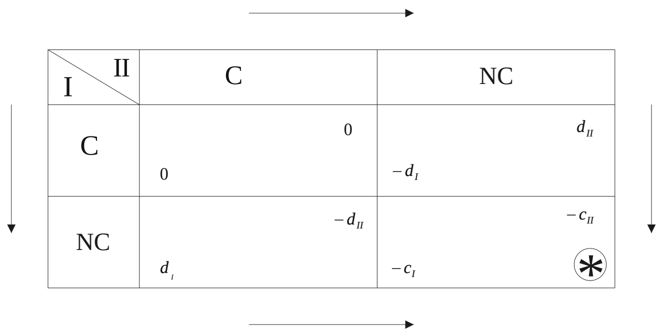

Figure 1: Normal form of the first game (no verification).

It should be mentioned that for both players one of the payoffs c or d could be normalized to one since the utility functions describing the payoffs are only determined up to affine transformations, but we did not do this for purposes of illustration and interpretation. For the sake of clarity it should also be mentioned that neither State would know if the other does not comply with the treaty before the existence of the weapons is revealed or the weapons used. Thus, the payoffs are meaningful only for planning purposes.

The method of incentive directions, by appropriate arrows also represented graphically in Figure 1, shows that (NC,NC) is the only pair of equilibrium strategies. Since the equilibrium payoffs are worse than those for the case that both states comply with the treaty, we have a so-called prisoners' dilemma: Both states will choose strategies which lead to worse payoffs than in case of treaty compliance, in other words, their equilibrium strategy would be to violate the treaty. It should be mentioned that because of the reasons mentioned before, these results would not change if the payoffs in the lower left and upper right box would not be anti symmetric, i.e., if the gain in case of unilateral non-compliance would be the same as the loss in case of unilateral compliance.

4.2 Second model: Verification with insufficient information

Now it is more appropriate to represent the non-cooperative two-person game, describing the second possibility mentioned in the introduction, in the *extensive form*, see Figure 2. It should be noted that the first model could also have been represented in this form.

Here, the payoffs to the two players are represented as row vectors at each terminal node. According to our assumptions, we have so-called chance nodes (Ch) which indicate that an illegal action of the first (second) State would be detected, with probability $\gamma_I (\gamma_I)$ and not detected with probability $1-\gamma_I (1-\gamma_I)$. In such case, the State would stop this illegal action so that its payoff would become

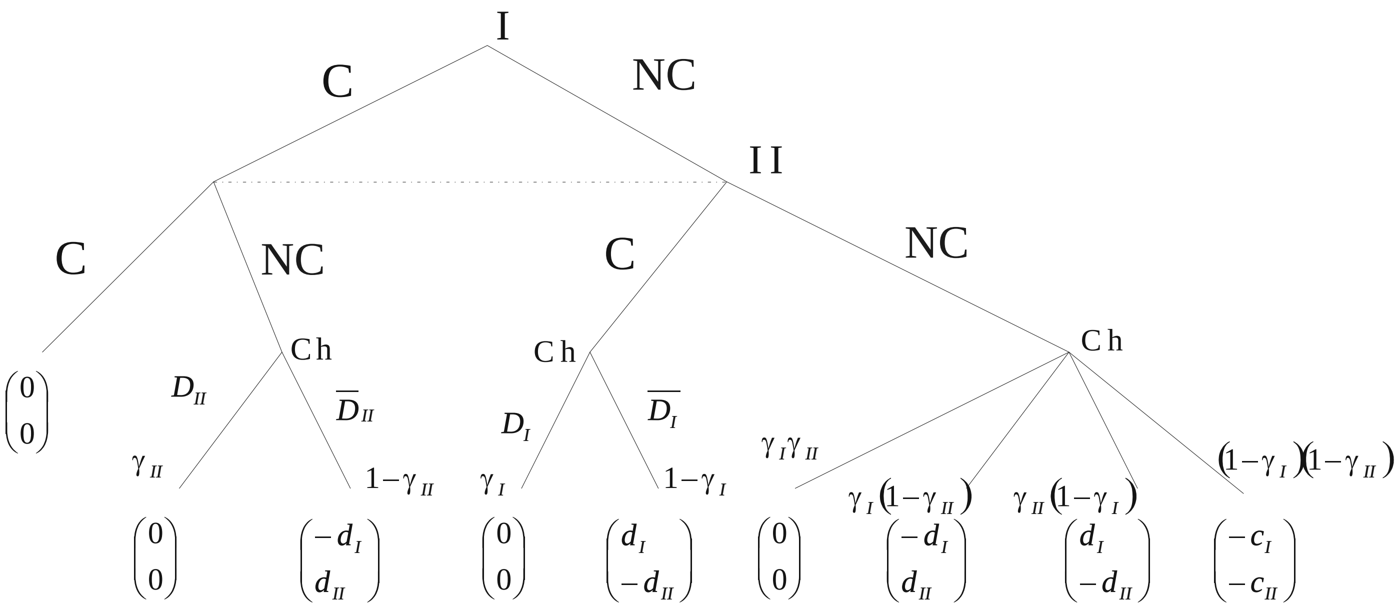

Figure 2: Extensive form of the second game (non-compliance may be detected, no consequences)

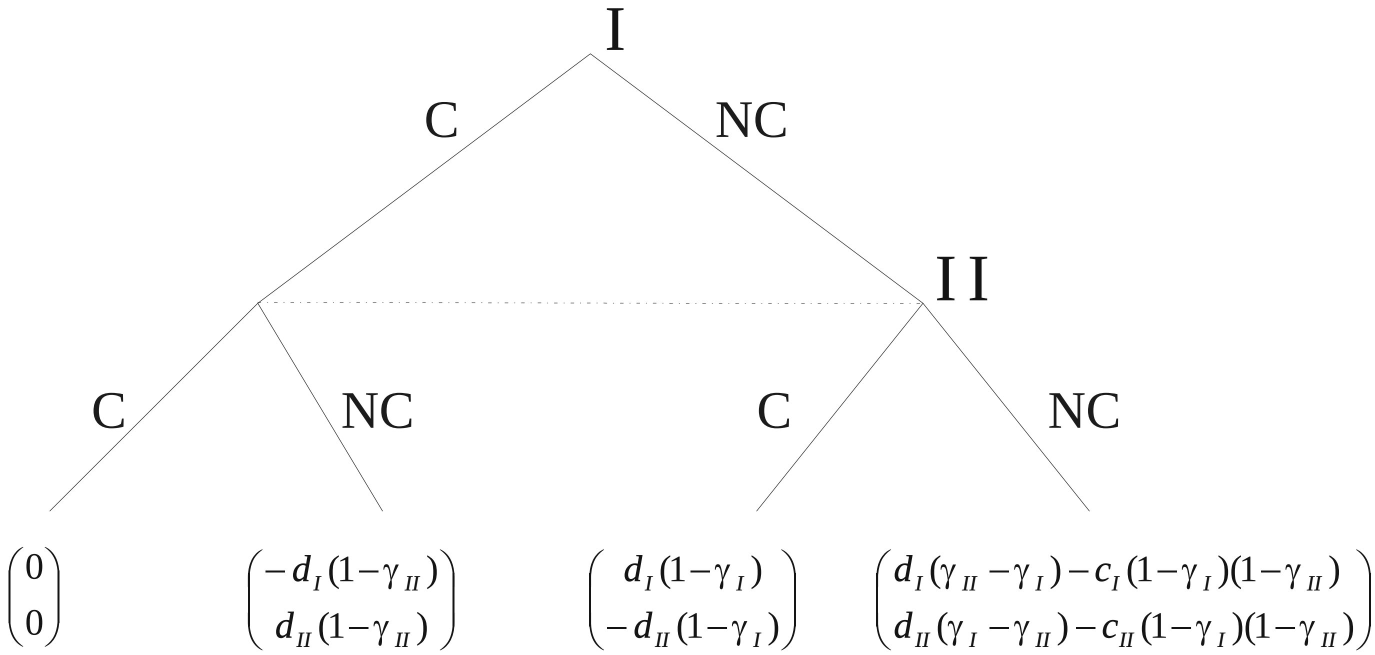

Figure 3: Reduced extensive form of the second game.

the same as if the State would have acted legally from the very beginning.

Taking the expected payoffs at the chance nodes, we arrive at a reduced representation of this game, shown in Figure 3. This game can again be represented as a normal form game shown in Figure 4. Note that for $\gamma_A = \gamma_B = 0$ we arrive at the simple game given in Figure 1.

I \ II	C	NC
C	II: 0; I: 0	II: $d_{II}(1-\gamma_{II})$; I: $-d_I(1-\gamma_{II})$
NC	II: $-d_{II}(1-\gamma_I)$; I: $d_I(1-\gamma_I)$	II: $d_{II}(\gamma_I-\gamma_{II})-c_{II}(1-\gamma_I)(1-\gamma_{II})$; I: $d_I(\gamma_{II}-\gamma_I)-c_I(1-\gamma_I)(1-\gamma_{II})$

Figure 4: Normal form of the reduced extensive form of the second game.

The method of incentive directions shows immediately that treaty compliance of both states is *not* an equilibrium solution of the game. In fact, (NC,NC) is the only equilibrium solution, since we have

$$-d_I\cdot(1-\gamma_{II}) < d_I\cdot(\gamma_{II}-\gamma_I) - c_I\cdot(1-\gamma_I)\cdot(1-\gamma_{II}) \quad \text{(2a)}$$

and correspondingly

$$-d_{II}\cdot(1-\gamma_I) < d_{II}\cdot(\gamma_I-\gamma_{II}) - c_{II}(1-\gamma_I)\cdot(1-\gamma_{II}) \quad \text{(2b)}$$

which is equivalent to

$$0 < d_I - c_I\cdot(1-\gamma_{II}) \text{ and } 0 < d_{II} - c_{II}\cdot(1-\gamma_I) \quad (3)$$

which is true due to our assumptions.

Two additional observations are important. First, for

$$\begin{aligned} -d_I\cdot(\gamma_I-\gamma_{II}) - c_I\cdot(1-\gamma_I)\cdot(1-\gamma_{II}) &< 0 \\ -d_{II}\cdot(\gamma_{II}-\gamma_I) - c_{II}\cdot(1-\gamma_I)\cdot(1-\gamma_{II}) &< 0 \end{aligned} \quad (4)$$

we again have a prisoners' dilemma type of situation (which holds, e.g., for equal detection probabilities for both States, $\gamma_I = \gamma_{II}$). Combining the two expressions in (4) we obtain

$$\frac{c_I}{d_I} < \frac{1}{1-\gamma_{II}} - \frac{1}{1-\gamma_I} < \frac{c_{II}}{d_{II}}. \quad (5)$$

If the detection probabilities in (5) are approximately equal, the equation may be interpreted as giving rise to prisoners' dilemma.

Second, we compare this equilibrium with that of the first game. For

$$-d_I \cdot (\gamma_I - \gamma_{II}) - c_I \cdot (1-\gamma_I)\cdot(1-\gamma_{II}) > c_I$$
$$-d_{II} \cdot (\gamma_{II} - \gamma_I) - c_{II} \cdot (1-\gamma_I)\cdot(1-\gamma_{II}) > -c_{II}\,, \tag{6}$$

we obtain,

$$\frac{-c_{II}}{d_{II}} < \frac{\gamma_I - \gamma_{II}}{\gamma_I + \gamma_{II} - \gamma_I\gamma_{II}} < \frac{c_I}{d_I}\,. \tag{7}$$

Again, if the detection probabilities do not differ too much, the second model shows "better" results than the first one in the sense that the equilibrium payoffs to both states are larger than in the second model.

As a result, we see that, in this case as well, the two States have no incentives to comply with the provisions of the treaty. They may, depending on the detection probabilities and payoff parameter ratios, again end up in a prisoners' dilemma type of situation.

4.3 Third model: Robust verification regime

The third case takes into account the imposition of sanctions. A State would suffer consequences if it would not comply with the provisions of the treaty and if the violation were detected by an international authority. In such a case, the payoffs are expressed as $-b_I < 0$ and $-b_{II} < 0$. The extensive form of this non-cooperative two-person game is represented graphically in Figure 5; it is very close to Figure 2 except for the payoffs. (In addition, we assume eventually that the detection probabilities are larger than in the second model even though we have used the same letters as before.)

Omitting the reduced extensive form which we obtain if we determine the expected payoffs at the chance nodes, we present immediately the normal form, see Figure 6. Again applying the method of incentive directions we see that now treaty compliance of both States is an equilibrium if the expected payoffs to both States in case of legal behavior are larger than those in case of illegal behavior,

$$0 \geq -b_I \cdot \gamma_I + d_I \cdot (1-\gamma_I) \text{ and } 0 \geq -b_{II} \cdot \gamma_{II} + d_{II} \cdot (1-\gamma_{II})\,. \tag{9}$$

For subsequent purposes, we note that (9) is equivalent to

$$\gamma_I \geq \frac{d_I}{b_I + d_I} \text{ and } \gamma_{II} \geq \frac{d_{II}}{b_{II} + d_{II}} \tag{9a}$$

Inequalities (9) give the conditions under which both States will behave legally. They will do so, if either the detection probabilities are large enough, or if the sanctions b, in case illegal behavior is detected, are

I \ II	C	NC
C	0 0	$d_{II}(1-\gamma_{II}) - b_{II}\gamma_{II}$ $-d_I(1-\gamma_{II})$
NC	$-d_{II}(1-\gamma_I)$ $d_I(1-\gamma_I) - b_I\gamma_I$	$-b_{II}\gamma_{II} + d_{II}(\gamma_I - \gamma_{II})$ $-c_{II}(1-\gamma_I)(1-\gamma_{II})$ $-b_I\gamma_I + d_I(\gamma_{II} - \gamma_I)$ $-c_I(1-\gamma_I)(1-\gamma_{II})$

Figure 6: Normal form of the reduced extensive form of the third game.

large compared to the advantages d, in case a violation is not detected. Furthermore, treaty compliance of both States is the *only* equilibrium, if (we present only the first condition, the second is the same if the numbering *I* and *II* of the two players is exchanged, *I*↔*II*)

$$-d_I \cdot (1-\gamma_{II}) > -b_I \cdot \gamma_I + d_I \cdot (\gamma_{II} - \gamma_I) - c_I \cdot (1-\gamma_I)\cdot(1-\gamma_{II}) \tag{10}$$

or, equivalently, if the probability of detecting the first State´s illegal behavior is large enough,

$$\gamma_I > \frac{d_I - c_I \cdot (1-\gamma_{II})}{b_I + d_I - c_I \cdot (1-\gamma_{II})} \tag{11}$$

Now it can be seen easily that

$$\frac{d_I}{b_I + d_I} > \frac{d_I - c_I \cdot (1-\gamma_{II})}{b_I + d_I - c_I \cdot (1-\gamma_{II})} \tag{12}$$

holds. This means that if (9a) holds, then treaty compliance of both States is the *only* equilibrium.

For the sake of completeness we note that for

$$\frac{d_I - c_I \cdot (1-\gamma_{II})}{b_I + d_I - c_I \cdot (1-\gamma_{II})} > \gamma_I \tag{13}$$

(and the same for $I \leftrightarrow II$) treaty non-compliance of both States is the only equilibrium, where as for

$$\frac{d_I}{b_I + d_I} > \gamma_I > \frac{d_I - c_I \cdot (1-\gamma_{II})}{b_I + d_I - c_I \cdot (1-\gamma_{II})} \tag{14}$$

(NC,C) and (C,NC) are equilibria - which means that there exists a third equilibrium in mixed strategies - and which causes an *equilibrium selection problem* which goes beyond the scope of this paper.

5. Conclusions

We have presented a model for analyzing and evaluating the performance of verification regimes. Verification of compliance is viewed as a decision-making process relying on data collected by monitoring

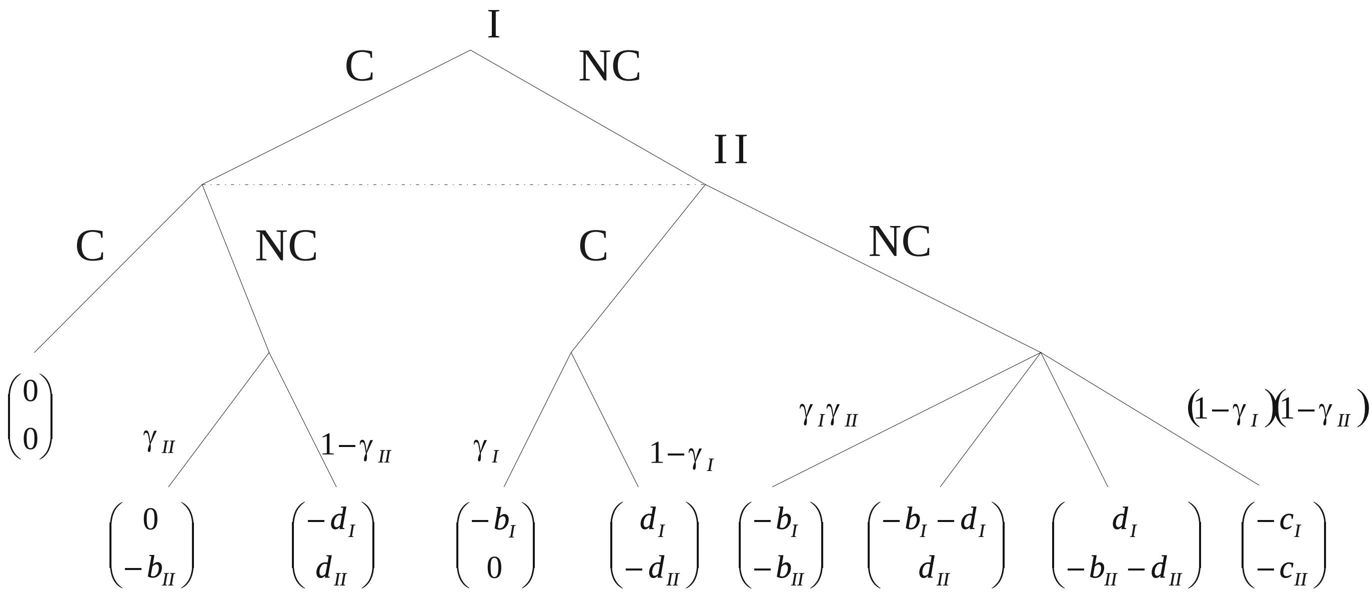

Figure 5: Extensive form of the second game (non-compliance may be detected, consequences).

systems. Taxonomy for analyzing the performance of monitoring systems has been developed. It has been shown that compliance cannot be treated as a binary variable, because the decision is based on statistical information which thererfore contains uncertainties. It would be more accurate and, probably, less controversial, if the verification regimes were designed to generate statements on compliance or non-compliance with some specified confidence levels. We have also shown that there is no substantive difference between verification and confidence-building measures. In the conventional usage, the former imply probability of detection one, while the latter imply a smaller, but unspecified, value.

To illustrate how such a model could be used, we have considered the simple case of the universe consisting of two States, which enter into an arms control agreement. Of the three cases considered, namely, absence of verification, verification with insufficient information and robust verification, only the last one leads under appropriate conditions to a desirable equilibrium: Both States are induced to comply with the terms of the treaty. Of particular interest is the second case of verification with insufficient information. Since no desirable equilibrium state exists, both States may enter into a prisoners' dilemma situation, which is similar to that of the case with complete absence of verification. In other words, verification with insufficient information is not any better than the absence of verification. The implications of such a conclusion can be profound bringing into question the utility of such regimes.

Admittedly, the considerations presented in the fourth sections are very abstract. Greater insight would be gained if these results were applied to verification regimes of existing treaties and, more importantly, to those under negotiation. Even if this approach were used in a qualitative manner, one could evaluate proposed verification measures in order to find out whether or not they would serve the objective of inducing States to legal behavior or, at least, help the detection of illegal behavior. For that purpose however, it would be necessary to connect the verification measures with the objectives of the treaty.

A more ambitious long term goal of our work is to develop it in a way such that it can be used constructively in the sense that treaty objectives and verification measures are matched - which means, *inter alia*, that they would have to be negotiated as a unit. In practice there are already a few examples. In the CFE treaty, e.g., only the quantity of heavy equipment like tanks, but not their quality, important as it may be, is subject to treaty provisions since only the former can be verified appropriately by means that were negotiated.

Although the objective of this paper has been the development of quantitative models, it should be kept in mind that, in practice, rigor should be tempered with common sense. Rules should not be so restrictive as to contradict some common sense idea of their necessity. They could become meaningless if suitable measures to enforce them could not be instituted.

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ESARDA activities

Monte Carlo benchmark exercises of the NDA Working Group

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Foreword: The last issue of the ESARDA Bulletin was a special issue entirely dedicated to a single paper. This decision could have surprised the ordinary Bulletin reader, also because of the choice of a quite specialised topic, not of broad interest, such as benchmark of simulation tools for NDA equipment. The ESARDA Editorial Committee feels the need to give a wider view about this topic in order to explain to the non specialist in Monte Carlo, why this subject is important for the Safeguard community and where this project is placed within the ESARDA activity. For this reason the chairman and the secretary of the NDA working group were requested to write this very short description on the working group activities in the field of physical modelling and numerical simulation.

Numerical simulation in NDA

Monte Carlo simulations applied to non destructive assay systems are commonly used as a design tool for NDA equipment, to optimise their performance and to predict their response in different kind of configurations, but also as a computational calibration technique [1,2].

The capability of computational tools has increased dramatically with the development of computer performances. In the case of NDA instruments for nuclear safeguards, it is possible to simulate the operation of the devices with mathematical models and reproduce the experimental data with a satisfying accuracy and with reasonable computing times. Computational modelling can provide fruitful improvements in the measurement procedures and must be considered as one of the available tools in experimental physics.

When considering the field of nuclear measurements applied to safeguard of nuclear materials, one of the most immediate among the several possible applications of computational modelling is the calibration of neutron counters. Calibration of NDA devices requires always a large experimental effort in terms of time and manpower and the availability of suitable calibration standards. The goal that we try to fulfil through computational modelling is a reduction both in the experimental work and in reference material requirements.

Benchmarking and validation of models

Notwithstanding Monte Carlo simulation has widely proven in the recent years the capability to model and accurately reproduce the response of NDA equipment, any project needs to pass through an intensive check procedure in order to assess:

- the general validity and limitations of the physical models used by the codes
- the quality of the physical data and parameters (such as nuclear cross sections)
- the applicability of the code to the specific problem

We generally refer to the first two steps as benchmarking and it is devoted to prove in a general way the quality of a methodology, whereas we call validation the third step and is application dependent.

The ESARDA NDA Working Group has always devoted a large interest to the application of Monte Carlo techniques to the numerical simulation of NDA instruments in general and neutron counters in particular. In this frame the working group has organised several benchmark exercises especially devoted to assess the potentiality and to demonstrate the capability of the technique.

Moreover under specific request of the IAEA, the NDA-WG is currently redacting a “Good Practice Guide in the use of Numerical Simulation in NDA”. The objective is to set up a system of behaviour rules to be followed by anybody who is using computational modelling applied to NDA techniques. The correct implementation of these rules will constitute a sort of quality certification that will allow helping in the acceptance of modelling results in measurement techniques and evaluation procedures.

Monte Carlo benchmarks of the ESARDA NDA-WG

Three benchmark exercises have been carried out in the last years in order to assess the capabilities of Monte Carlo to reproduce the experimental data:

- one was on a simple geometry [3]: a point californium source placed at a fixed distance from a slab detector with interposed layers of moderator (polyethylene) and absorber (cadmium). The purpose was to analyse the influence of the main basic physical parameters (influence of fission spectrum, thermal treatment, cross section dataset,…
- another one dealt with the comparison of models for the prediction of the real coincidence rates from a reference PWR fuel assembly measured with an active neutron collar [4]
- the most recent one intended to model a passive multiplicity counter and the results of this exercise have been described in the final report that has been object of the special issue of the ESARDA Bulletin [5].

A follow-up of this latter benchmark is now ongoing. The idea is to repeat the exercise with an experimental pulse train acquired in LIST mode, instead of a simulated one. The goal is to compare the available software for LIST mode data analysis in view of possible future developments of neutron counting towards the abolition of shift register analysers and direct acquisition and processing of pulse trains by a PC.

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International Academic Education on Nuclear Safeguards

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Foreword

This paper contains large excerpts of an article already published in the INMM and the IAEA conferences 2006. It is completed by taking into account the new developments decided by ESARDA and the organisation of the March 2007 course.

Abstract

The knowledge retention problem in the nuclear field was acknowledged by the OECD in 2000. The United Nations study on disarmament and non-proliferation education (2002) made detailed recommendations for urgently required improvements. ESARDA, the European Safeguards Research and Development Association (http://www.jrc.cec.eu.int/esarda/), reacted to that with a strategy to tackle the problem and created a Working Group on Training and Knowledge Management (ESARDA WG TKM). The final objective of the ESARDA WG TKM is the setup of course modules to an internationally recognised reference standard.

This project is in line with the movement of establishing a European curriculum for Nuclear Engineering. Teaching in the Nuclear Safeguards field is indeed strongly influenced by national history so the objective of the course is to provide homogeneous material in Nuclear Safeguards and Non-Proliferation matters at the European level. The harmonization of a European curriculum is driven by factors of economy and safety. In the Nuclear Safeguards field in Europe, the harmonization force is the Euratom Treaty that any nuclear facility should observe.

This paper reports on the feedback of the course that was held by some of the leading experts in the field of Nuclear Safeguards in Europe. Its content deals with the general background of safeguards legislation and treaties, the nuclear fuel cycle, various safeguards techniques, verification technologies and the evolution of safeguards. The audience - 40 university students and 7 young professionals (STUK and JRC) – from 12 different European countries was highly interested and provided positive feedback. The course has been introduced in the

course database of the European Nuclear Education Network on the website http://www.neptuno-cs.de and recognised as academic course of two credits under the European Credit Transfer System (ECTS) by the Belgian Nuclear higher Education Network.

In addition this paper announces the future perspectives with the intention of ESARDA to have this course on yearly basis, in particular the course of March 2007. The standard part of the course will be documented by a syllabus with ESARDA label. Master degree students of European universities that share the ECTS, are evaluated at academic level with examination and essay. In this way the course can be introduced in the academic curriculum of a nuclear engineer as optional course for a European Masters Degree in Nuclear Engineering, recognised by the European Nuclear Education Network (ENEN).

1. Introduction

The situation of the nuclear industry in the last decades of the twentieth century had consequences in the education of nuclear engineers. European universities did no longer register a minimum number of students for a Master Degree in nuclear engineering. Also the US National Research Council (1990) reported a strong reduction in nuclear engineering students, an extremely high age of faculty members and shutdown of nuclear research facilities at American universities. The OECD (2000) expressed their major concern about the diminishing and disappearing nuclear knowledge. The International Atomic Energy Agency, the Nuclear Energy Agency of the OECD, the World Nuclear Association of Nuclear Operators and the World Nuclear Association therefore founded the World Nuclear University with 29 nuclear research centres as institutional participants, organising a nuclear summer course on a yearly basis. This international university organisation focuses on major academic nuclear disciplines with a non-European dimension. However, it neither copes with the European brain-drain problem nor it includes teaching of Nuclear Safeguards principles. Therefore, firstly, the European Commission called for a European solution for the nuclear retention problem, which was developed with the European Nuclear Engineering Network. Secondly the European Safeguards Research and Development Association (ESARDA) did extend their mandate on enhancing the efficiency of Nuclear Safeguards systems and developing new techniques with an educational role.

2. The European Nuclear Education Network Association

The European Commission launched an initiative for addressing this knowledge retention problem. This was done under the 5th Framework Programme for Research and Technological Development – FP5 (1999-2002). This resulted in setting up the European Nuclear Engineering Network – ENEN. In parallel to this international project some national satellite networks were established, such as the Belgian Nuclear higher Education Network – BNEN, the Italian Interuniversity Consortium for Research and Technology on Nuclear Energy – CIRTEN, the UK's Nuclear Technology Education Consortium – NTEC, and the German Education Centrum for Nuclear Technology – TÜV Nord Akademie. According to Van Goethem (2005) the strategy for safeguarding nuclear education and training is based on three pillars: (a) common qualification, (b) mutual recognition, and (c) mobility of scientists and students.

The FP5-project ENEN is followed up on the one hand by the NEPTUNO[1] project under the 6th FP (2003-2006) and on the other hand with a sustainable European Nuclear Education Network Association - which took over the acronym ENEN. The major objective of this Association is the reinforcement of the three above mentioned pillars. Activities focused on the work of five specific committees: (i) Teaching and Academic Affairs, (ii) Advanced Courses and Research, (iii) Training and Industrial Projects, (iv) Quality Assurance and (v) Knowledge Management. The history and the current organisation of this international Association are described by Giot (2006).

Since 2003 the European Nuclear Education Network Association ENEN provides an educational programme for the specialisation in the nuclear field. Students are expected to have already an engineering or equivalent university diploma. Moreover, their nationality should be from a country that signed the Non Proliferation Treaty. The complete programme is taught at European universities, profiting from the recognition of the long-established universities, from the fact that only universities can award an academic diploma, and from the pool of professors that are selected and financed by the universities. The contents of several courses are also industry oriented, to satisfy also the sponsors and beneficiaries, the European nuclear industry. In 2005, the first four students obtained the Master Degree in Nuclear Engineering.

1 NEPTUNO represents the Nuclear European Platform for Training and UNiversity Organisations as described on website http://www.sckcen.be/neptuno/

The Master Degree takes a minimum of one academic year (60 ECTS[2] credits – corresponding of one final year of university studies with 5 courses of 6 ECTS – 5 courses of 3 ECTS and a thesis of 15 ECTS) for accomplishing these studies. The student can select these courses out of a large variety offered by 24 universities. The database of courses is open for consultation on the website http://www.neptuno-cs.de. An analysis of the ca.300 courses available shows that no university offers a course on Nuclear Safeguards and/or Non-Proliferation in the curricula at the engineering and exact science faculties.

3. ESARDA Strategy for Nuclear Safeguards Education

This shortcoming on education in Nuclear Safeguards was discussed by ESARDA and a strategy to tackle this problem has been defined by its Steering Committee in several steps. As published by Bril (2004), ESARDA intends to propose a continuum from the glossary that explains shortly the various concepts and objects used in the Nuclear Safeguards fields, to a specialised course entirely devoted to teaching Nuclear Safeguards concepts, methods and techniques. The latter are also addressed with a medium-size document of the so-called technical sheets. Both glossary and technical sheet examples can be found on the ESARDA website. The Course Modules initiative was launched in September 2002. Upon positive evaluation of the demand and interest for these Course Modules, a first task group was officially set up in May 2003 with Messrs. Gottard Stein, Klaas van der Meer and Sergio Guardini (replaced by Ms. Greet Maenhout in 2004). This group, called the Training and Knowledge Management Working Group – TKM-WG, started preparing the course modules in 2005.

4. The 2005 Prototype of a three-day Nuclear Safeguards Course

Upon request of the students from the Belgian Nuclear Education Network a first Nuclear Safeguards and Non-Proliferation course was established by the JRC in collaboration with the SCK-CEN Belgian research centre. The course was held at JRC, Ispra site, 1-3 March 2005. The course was attended by 10 university students and 8 young professionals, as shown in Fig. 1. The feedback of the students and the experience at the JRC and the SCK-CEN was positive. Details on the course can be found in Janssens-Maenhout & Poucet (2005) and van der Meer et al. (2005). The ENEN students made a report on the total content of the safeguards course and the students from the University of Ghent worked out a study on the illicit trafficking trend and their evolution from before 1990, between 1990 and 2001, and in the post-era.

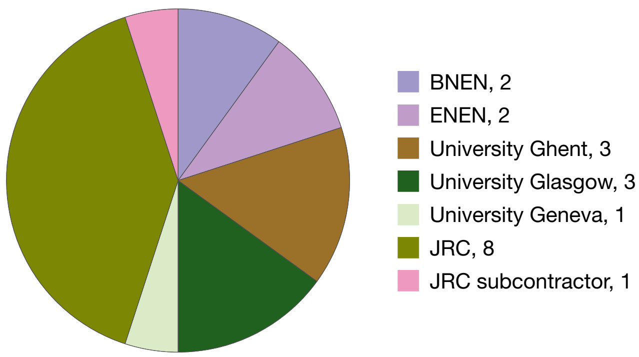

Fig. 1: Distribution of students attending the Safeguards course in Ispra, 1-3 March 2005

5. The first ESARDA Course 2006 on Nuclear Safeguards and Non Proliferation

5.1. Content

The first ESARDA course was discussed in content and organization by the ESARDA Training and Knowledge Management Working Group and guaranteed a complete Nuclear Safeguards overview, presented by the major stakeholders (nuclear industry, research centres and regulatory authorities) taking into account the presence of the various nationalities in the EU.

Fig 2 represents the final course schedule for the three first days of the course with theoretical lectures and a class room exercise.

The course schedule is structured in a standard part, given during the first days, that covers:

- an indication of the different Nuclear Safeguards aspects, from legal point of view and from industry point of view with an overview on the arms control treaties;
- an insight view on proliferation aspects of the fuel cycle, while pointing to proliferation sensitive installations and the efforts to prevent the spread of nuclear material and nuclear technology for manufacturing nuclear devices;

[2] The so-called 3 ECTS = 1 teaching module at university with 20 hours of lecture and 10 hours of exercises, laboratory sessions and seminars. ECTS stands for "European Credit Transfer System", defined in the Sorbonne-Bologna process for harmonisation of the university courses (need for exchanging students, e.g. under ERASMUS). (Students can follow courses at other universities and it is well-known what their value are).

1	D1	J. Joly	Introduction to Nuclear Security
2	D1	C. Jorant	Nuclear Fuel Cycle and Non-Proliferation Aspects
3	D1	T. Jonter	History of Nuclear Safeguards and non-Proliferation
4	D1	A. Pouchet	Overview of Treaties: NPT, CTBT, ...
5	D1	M.Hunt	Exercise: how to setup a verification of a certain region
6	D1	C. Jorant	Proliferation and Control: Impact for industry
7	D2	B. Burrows	Basic principles on Nuclear Safeguards (SSAC, NMAC, ...)
8	D2	M. Franklin	Accountancy from a statistical perspective
9	D2	P. Funk	Monitoring (C/S, Processes, ...
10	D2	P. Schwalbach	On-site inspections
11	D2	M. Kalinowski	Import/Export Control
12	D2	K. Mayer	Destructive Assays and Nuclear Forensics
13	D2	M. Kalinowski	Environmental Monitoring
14	D3	J. Baute	Information Collection an Analysis
15	D3	J. Baute	Iraq Case Study
16	D3	P. Peerani	Non-Destructive Assay, Inspection Equipment (Neutron/Gamma)
17	D3	L. van Dassen	New Challenghes in Security: Illicit Trafficking
18	D3	M. Hunt	Exercise: verification of a region – presentation of results
19	D3	G. Maenhout	Some Proliferation Question

Fig. 2: Schedule of the first ESARDA Course on Nuclear Safeguards and Non Proliferation in Ispra, 6-9 March 2006.

- a discussion of the non-proliferation system and its historical evolution, answering whether a functioning nuclear non proliferation system exists today in Europe;
- a description of verification systems with safeguards principles addressing the logic of nuclear material accountancy and control and including statistical aspects of the auditing of a nuclear material accountancy
- an explanation of the inspection philosophy (incl. EURATOM inspection strategy) and of some methodological aspects of monitoring and of containment and surveillance
- an overview on major technical means and inspector tools (Non Destructive Assay, Gamma Spectrometry, Destructive Analysis), incl. novel technologies such as environmental sampling
- an outline of the import and export control issue
- an indication about the analysis of additional information exploring open and other sources and satellite images

This was then completed with some topical lectures addressing:

- the Iraq case study, incl. experience of the inspections by IAEA in collaboration with the United Nations Monitoring, Verification, and Inspection Commissions
- combating illicit trafficking of nuclear and radioactive material, incl. nuclear forensics

On the fourth day practical visits were organised to the following four JRC laboratories:

- the Performance Laboratory (PERLA) with an extensive collection of well-characterised nuclear reference materials and non destructive analysing techniques,
- the TAnk Measurements Laboratory (TAME) for total inventory calibrations, densitometry and solution monitoring,
- Seal and Identification Techniques Laboratory (SILAB), for safeguarding with authenticated seals all nuclear material (such as fuel assemblies) in storage places or containers or transport casks, and
- the Surveillance Laboratory with 2D/3D laser surveillance systems and 3D image reconstruction tool for remote verification.

5.2. Participation and feedback

The course was attended by 47 participants, of which 40 students from various universities, spread over 12 different European countries and from 7 young professionals (from STUK and JRC). There were five students from the New Member State Hungary and the two acceding countries, Bulgaria and Romania. Fig. 3 presents the distribution of the 47 course attendees with their affiliation. The course was highly appreciated by all participants with positive feedback on the content of the lectures, the exercise and the practical demonstrations during the visits. After each lecture, lecturers had the opportunity to answering to the many questions addressed by the students.

As feedback the students suggested to spread the course schedule over five days, including more exercises, also hands-on exercises in the labs, to be alternated with theoretical courses. Many students were surprised by the many different actors in the Nuclear Safeguards world and the "slang" – professional jargon – being used. It is desired to address this in more detail. In general students preferred the lectures on more technical topics.

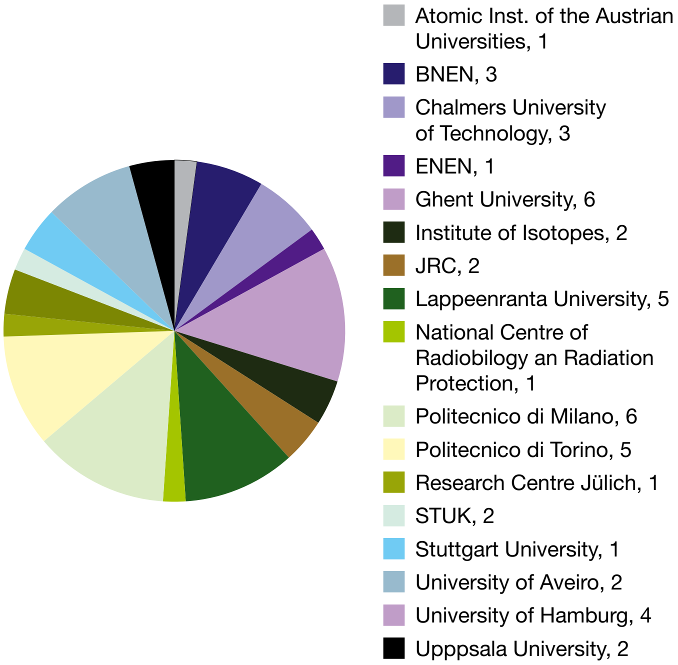

Fig. 3: Distribution of students attending the first ESARDA Nuclear Safeguards course in Ispra, 6-9 March 2006

However, coupling the technical issues with the international legal aspects (leading to politics) illustrated by real facts opened significantly their perception.

6. The ESARDA Nuclear Safeguards Course of March 2007

6.1. Course schedule spread over five days

The 2007 ESARDA course has been announced from 5 till 9 March 2007 in JRC Ispra. As in the 2006 course, a similar standard part will be covered in March 2007 by mainly the same lecturers, during the first three days. The last two days focus on some topical lectures and foresee some more time for the exercise, as shown in the new course schedule of Fig. 4. A more detailed outline of the course is available at the ESARDA website, on the page of the TKM-WG (http://esarda2.jrc.it/internal_activities/WC-MC/index.html).

6.2 The ESARDA course material

As mentioned earlier, the topic of Nuclear Safeguards is not covered by any European University. Creating a most necessary Nuclear Safeguards culture among nuclear engineering students is a challenge similar to the one that resulted, 20-30 years ago, in creating the safety culture, today universally promoted. So ESARDA decided to bridge this educational gap by elaborating a specific course module. The proposal will include a detailed syllabus as well as a set of presentation material and references. The 2006 course has successfully created a set of teaching documents, some of them based on existing presentations, others having been created for this purpose.

Given the working structure of ESARDA, all its Working Groups were requested to provide material for the different lectures. They are including the redaction and revision of course material in their normal range of activities. In that way it is expected to build progressively a repository of state-of-the-art didactic material, authored by the small community of competent specialists in each field, upon which any qualified lecturer on a given topic will base his/her lectures for a given course session. The recognised competence of the ESARDA Working Groups ensures a high standard of quality for the course material from which students, lecturers or external public benefit. Moreover the lectures cover a general view shared by the ESARDA Working Groups and are not depending on individual lecturers.

The Working Groups C/S and NDA have already begun to work: in 2007, for the first time, the course will present, in these two domains, didactic material already reviewed, by these Working Groups.

In addition, ESARDA will then own the intellectual property rights of the didactic, teaching and reference materials. This will considerably ease the issue of availability of the material to lecturers others than the authors.

6.3. The international dimension

Profiting from the extension of the course, an extra international dimension has been added with a lecturer from the Pacific North-West National Laboratory and a lecturer from the Monterey Institute, Centre for Non proliferation Studies, specialised in the Commonwealth of Independent States. Moreover the course will also welcome some Russian university students, but the major participation will remain from European students.

7. Conclusions

The first ESARDA course was a success, shown by the numerous participants and the positive feedback. The course will be yearly repeated in Spring and aims at a recognition of this course with 3 ECTS in an academic curriculum by the BNEN (ENEN). This requires the establishment of a syllabus with ESARDA label on the standard part.

The course will include in addition topical lectures that may vary from year to year, in order to address also actual issues and to cope with suggestions from participants. Participation of the course is open to both university students and young professionals. ESARDA Parties and associate members have largely supported the course by seconding most of the lecturers. The future of the course depends upon their continuous commitment to it.

The ESARDA TKM Working Group has received the mandate to shape the ESARDA course. For that purpose it relies on the knowledge of all ESARDA WGs in their respective field of competence.

Aside the course itself, another deliverable will be the course syllabus to be published as a special issue of the ESARDA Bulletin.

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News from ESARDA members

Experiences in Preparing the Implementation of the Additional Protocol in Germany

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Abstract

The 13 Non-Nuclear Weapons States in the European Union have concluded with the IAEA a common Additional Protocol to their Safeguards Agreement INFCIRC/193 and are preparing its implementation in their countries. The German Government decided to transfer, as far as possible, the executive responsibility under the Additional Protocol to the European Commission. The necessary legal actions for ratification and implementation of the Additional Protocol had been completed in February 2000.

The nuclear fuel cycle in Germany has changed considerably over the years. Many installations are closed-down or converted to non-nuclear activities. Moreover Germany has taken the decision to phase out the electricity production by nuclear energy. Therefore, the preparation of the initial declaration under the Additional Protocol becomes difficult and requires a large effort for both Germany and the European Commission. The activities undertaken so far, the current status and experiences gained in preparing for the implementation will be presented[1].

Keywords: Additional Protocol; Germany; Expanded Declaration

1 Introduction

During the IAEA General Conference in September 1998, Germany together with the other member States of the European Union signed the Additional Protocol (AP) to the Safeguards Agreement INFCIRC/193. As all EU member States are also members of the European Atomic Energy Community (EURATOM), any agreement on safeguards becomes a tripartite one between EURATOM, the State/s and the IAEA. The 13 EU Non-Nuclear Weapons States (NNWS) have concluded a single Additional Protocol with the IAEA.

The Protocol signed by the EU states based on the Model Additional Protocol INFCIRC 540 takes the EU specific situation of a single market and the responsibility of Euratom into account, and therefore contains a third annex. The last paragraph of this annex is of special importance for Germany. According to this paragraph the state is able to transfer certain responsibilities under the Additional Protocol to the EU Commission. To a great extent, Germany makes use of this option laid down in Annex III.

2 The Legal Framework

In Germany, national interests and affairs as well as R&D activities in the safeguards field are within the responsibility of the Federal Ministry of Economics and Labour (BMWA). From the political side, the BMWA is in charge of implementing the Additional Protocol.

The operative responsibility for safeguards in Germany has been completely assigned to the European Commission. Therefore, Germany has no national safeguards office of its own. These tasks are executed by the respective departments of the European Commission. Moreover, the operators of facilities subject to safeguards are obliged to directly report to the Safeguards department of the European Commission (Euratom), and Euratom forwards the necessary reports to the IAEA. Euratom deals directly with the organisations and operators concerned without interacting with a state organisation.

The German government has – like other member states - informed Euratom about its intention to make use of the possibility offered in Annex III to entrust to the Commission the implementation of provisions under the Protocol. The German parliament has passed two laws to establish the legal framework for the implementation of the Additional

[1] General disclaimer: The views expressed in this paper are the individual views of the authors, and are not meant to represent the official view of their organisations.

Protocol. The first law, published in the official federal gazette, the Bundesgesetzblatt, on February 7, 2000, covers the formal consent to the Additional Protocol, and the second law, called 'Ausführungsgesetz zum Verifikationsabkommen und zum Zusatzprotokoll' and published one day later, covers the implementation regulations.

The allocation of the duties resulting from the Additional Protocol, i. e. which provisions Germany will entrust to the Commission of the European Communities and which will remain with the German government, is laid down in the implementation law. For instance, all reporting tasks under Article 2 of the Additional Protocol are assigned to Euratom with the exception of Article 2.a.ix (reporting on exports end imports of Annex II items) and Article 2. a.x (the general plans for the succeeding ten-years period). That means, that the implementation law obligates the operators to directly report to Euratom the relevant information and Euratom will collect, prepare and finally submit this information to the IAEA. BMWA will support Euratom in the initial phase to carry out this work and will execute enforcement where necessary.

3 The Development of Nuclear Activities in Germany

Research and development in the field of civil use of nuclear energy has been initiated in Germany in 1955 after the Federal Republic of Germany officially had renounced the development and possession of nuclear weapons and had become a sovereign state. The research and development programme was, right from the beginning, based on an intensive international co-operation and included the construction of several prototype reactors, the elaboration of concepts for a closed nuclear fuel cycle and for the final storage of radioactive waste in deep geological formations.

In the following year, four nuclear research centres were founded:

- KFK in Karlsruhe (Kernforschungszentrum Karlsruhe) with the foundation task of reactor development, later-on research in all areas of the fuel cycle;
- GKSS in Geesthacht (Gesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt) with the task of carrying out research relating to nuclear-powered vessels;
- KFA in Jülich (Kernforschungsanlage Jülich) with the foundation task exploit i. a. nuclear energy for peaceful purposes;
- ZfK in Rossendorf (Zentralinstitut für Kernforschung).

The Central Institute for Nuclear Research (ZfK) was founded in the former German Democratic Republic.

Many universities were equipped with research reactors. In 1958, the first German nuclear power plant, the 15 MWe experimental nuclear power plant (VAK) in Kahl, was ordered from General Electric and AEG, which entered into operation in 1960. The development of reactors in Germany began in 1961 with the order to BBK/BBC for the 15-MWe high-temperature pebble-bed reactor (Arbeitsgemeinschaft Versuchsreaktor (AVR)) in Jülich.

A period of intensive activities in research and development of different reactor types began and the construction of large capacity units for industrial power production started. In 1969, Siemens and AEG founded the Kraftwerk Union (KWU) by merging their respective nuclear activities. Here, the development of German pressurised water reactors began, and it ended after several steps with the standardised 1,300-MWe PWR, the "Konvoi". The last nuclear power plants built in Germany were three of these Konvoi-type plants, which were commissioned in 1988.

In the Federal Republic of Germany, one demonstration prototype of each was built for the high-temperature reactor (THTR-300) and the fast breeder reactor (SNR-300) with a capacity of 300 MWe each. The THTR-300 in Hamm-Uentrop reached criticality in 1983, and was shut down for decommissioning in 1988 having achieved 220 days of full-load operation only. The SNR-300 project in Kalkar was terminated in 1991 without having reached criticality.

Starting in the nineteen-seventies, at the latest after the Harrisburg accident in 1979 and then finally

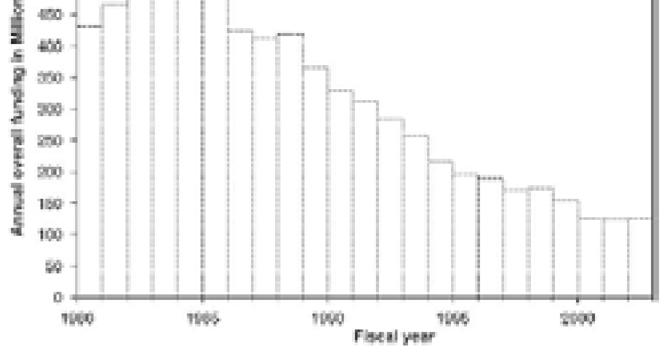

Figure 1: Government funding of nuclear research

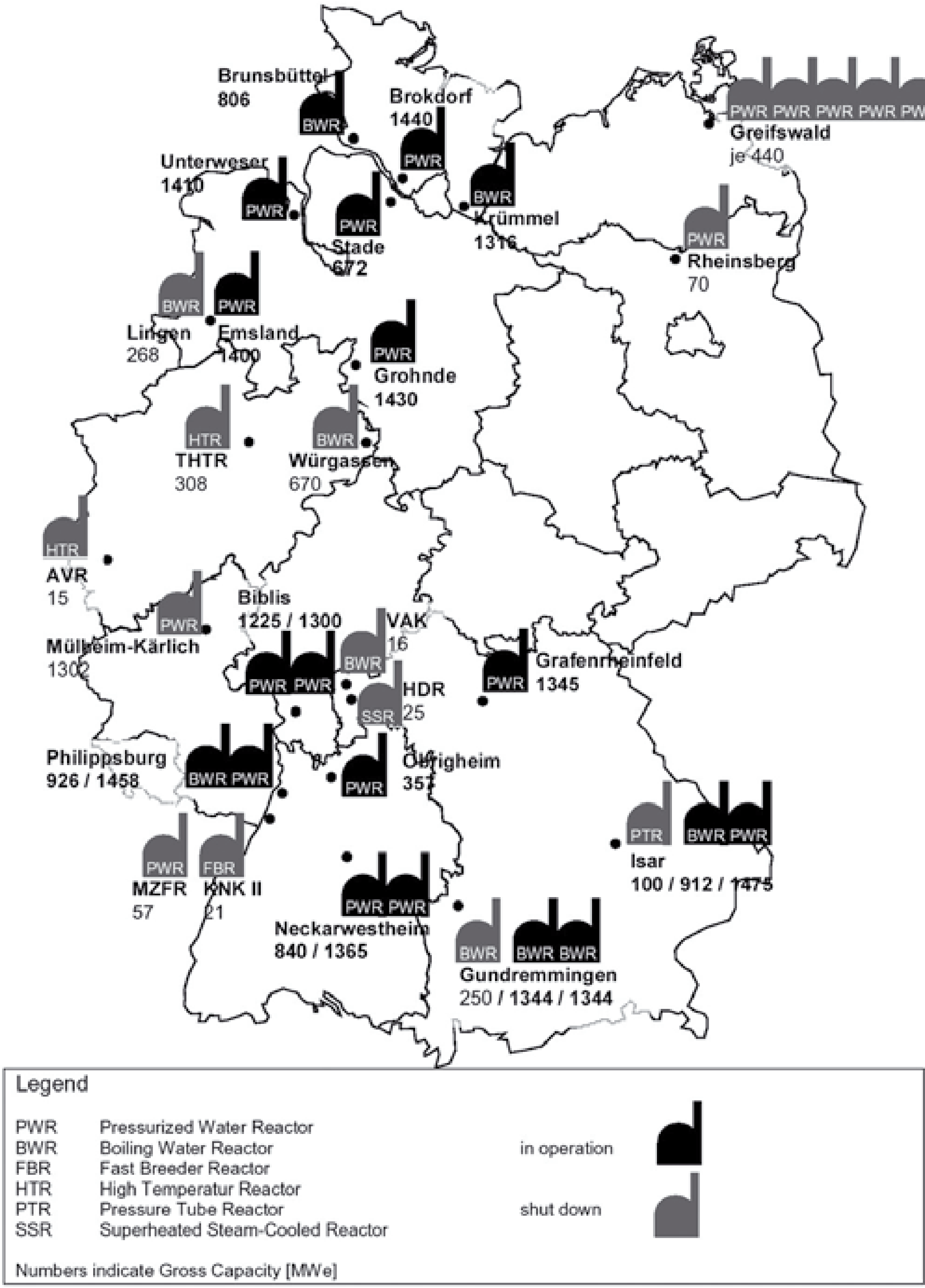

Figure 2: Power reactors in Germany (shut down here means: closed down or under decommissioning or decommissioned)

after the disaster of Chernobyl in 1986, scepticism towards nuclear energy grew in parts of the German population and led to massive protests against nuclear projects. This contributed in the following years to a decrease in the engagement of the German government and industry in nuclear activities.

The decline of nuclear research projects and funding is illustrated by the following graph which shows the history of government funding in the field of nuclear research from 1980 to 1998 (with planned figures from 1999 to 2003).

After the general elections in September 1998, the new German government declared its will to phase-out the use of nuclear energy for electricity production and to terminate all governmental funding of R&D activities in this field. An arrangement between the Federal Government and the power utilities was achieved on 14th June 2000 (signed on 11 June 2001), paving the way for the gradual closing down of the currently operating nuclear power stations.

Part of this arrangement is the clear obligation that the dynamic damage precaution according to the state of the art in science and technology required by law, and thus also the internationally required high level of safety have to be maintained during the remaining operating lives of the nuclear power plants.

4 The Present Status of Nuclear Installations in Germany

Currently, 19 nuclear power plant units are in operation at 14 different sites. Figure 1 shows the geographical location of the individual sites. Altogether, 22 nuclear power plants have been decommissioned or abandoned as projects during the construction phase. From these, 14 units were closed down for decommissioning after operating lives between 0.5 and 25 years. They are currently being dismantled with the aim of complete removal or prepared for safe enclosure, or they are safely enclosed. The majority of these reactors are low-power reactors from the early days of nuclear energy usage. Two further nuclear power plants have already been dismantled completely, and the respective sites have been recultivated and became a “green meadow”.

The other nuclear installations are research reactors, facilities of the nuclear fuel cycle and for the treatment and final disposal of radioactive waste. A uranium enrichment plant at Gronau and a fuel fabrication plant for LWR fuel elements at Lingen are in operation. The former NUKEM and HOBEG fuel fabrication plants, for research reactor fuel and for THTR/AVR fuel, and the former Siemens uranium and MOX fuel fabrication facilities at Hanau as well as the pilot reprocessing plant at Karlsruhe (WAK) are under decommissioning up to complete dismantling. The licensing procedure for the pilot spent fuel conditioning plant (PKA) at Gorleben was completed in December 2000 with the granting of the third partial construction license including the operation license. According to the arrangement between the Federal Government and the power utilities of 14 June 2000, the use of the plant shall be limited to the repair of defective containers.

5 Experiences Concerning the Implementation of the AP

5.1 Experiences Related to Sites

With the implementation of the Additional Protocol, also the nuclear past of a country has to be accounted for, as it affects the activities of the Agency and the obligations of the State in many aspects. The intensive nuclear activities in Germany in the past decades had led to quite a large number of facilities and locations outside facilities (LOFs) under IAEA safeguards. Although many of these installations, with the decline of nuclear activities in Germany, were closed down, decommissioned or converted to non-nuclear uses, they still exist in the records, and their development has to be sorted out. Under the traditional safeguards regime under INFCIRC/153, often these installations were not followed when the location was closed down, i. e. with the removal of the nuclear material, even though under the “Strengthened measures” approved by the IAEA Board of Governors in 1992, Agency policy has been to continue to do DIV on “closed-down” facilities until the facility has been verified as being “decommissioned” for Safeguards purposes. Under the AP, closed down facilities still have to be reported as a ‘site’, as long as they are not confirmed as decommissioned for safeguards purposes. So, one big task in preparing for the implementation of the Additional Protocol was, and still is, to follow up on the actual status of installations that are kept as ‘closed down’ in the records.

In the last year, Euratom spent a considerable effort to confirm, together with the Agency, the decommissioned status of former facilities and LOF’s in the research centres Jülich, Karlsruhe and Rossendorf. After visits to the locations, the decommissioned status was definitely confirmed for 2 former installations in Rossendorf and 3 in Jülich, for 17 installations in Karlsruhe the confirmation process is under way but not yet finalized.

In this context, another big task currently under way is to establish the actual use of nuclear material in LOFs. With the general decline of nuclear activities in Germany, installations that worked in the past on activities related to the nuclear fuel cycle disappeared or switched to activities where their expertise is now used for non-nuclear purposes, like environmental, medical, hydrological, agricultural, or similar applications. Nuclear material in non-nuclear use can qualify for an exemption from IAEA safeguards and, thus, considerably reduce the reporting effort for the state under the AP.

The task is to establish for all LOFs concerned the actual use of the nuclear material, to check whether it qualifies for an exemption under the safeguards Agreement and, should this be the case, to request the exemption. In the past, Euratom advised the operators against applying for an exemption, and therefore this options was hardly used until now.

Concerning the nuclear research centres, the decrease of nuclear R&D activities and funding have called for a rigid change in the profile of research activities. New institutes and new research facilities devoted to new research fields such as computer science, genetic engineering, material research, etc. were accommodated on the same premises and often in the same buildings formerly used in nuclear research activities. This led to a purely spatial co-location of very different research installations with sometimes quite sensitive scientific or commercial know-how and with no functional relation to the few remaining nuclear activities in the centres. The same holds true for industrial sites which in former times were exclusively devoted to nuclear activities, such as at Hanau or Karlstein, and which were converted into diversified industry and technology parks now housing a wide range of different enterprises, from mail order business storehouses to civil engineering offices. Here, the issue of the site definition in the sense of Article 2.a.iii of the AP plays a significant role. (These aspects will be discussed in a Euratom presentation at this symposium.)

5.2 Experiences Related to Government Funded Nuclear R&D

5.2.1 Research Policy Objectives

As a result of the Federal Government's decision to phase out the use of nuclear power, a new situation has emerged for research and technology funding in the field of nuclear energy research. Research activities now primarily focus on safety aspects. This involves maintaining a minimum level of expertise for supporting and monitoring the phase-out of NPP operations, as well as closely observing and analysing, and providing advice on other countries' safety philosophies. Precautionary, application-oriented activities to ensure long-term safety in the disposal of radioactive waste constitute another important task. The nuclear energy research activities of the Jülich (FZJ) and Karlsruhe (FZK) research centres and also universities, continuously reduced in scope over the last few years, are confined to precisely this field.

Research activities in the field of reactor safety will continue to focus on the following elements:

- Improving the models for the quantitative and qualitative description of material behaviour and failure modes of reactor components under complex load cycles as well as the models for operation under extreme loading conditions;
- Evolving assessment methods in reactor physics;
- Improving the methodological basis and computer programmes required for assessing safety conditions at nuclear facilities.

5.2.2 Research Activities in 2001

According to these research policy objectives, state-sponsored R&D in the field of nuclear engineering in 2001 was oriented at nuclear safety and nuclear waste management issues, albeit on a comparatively low level. At the Karlsruhe Research Center, the activities of the "Nuclear Safety Research Project" are aimed at establishing a new quality of light water reactor safety, derived from the more stringent requirements for future nuclear power plants (amendment of the Atomìc Energy Act of 1994). The research was carried out within the framework of cooperation agreements with the industry as well as with partners of the European Union and non-European facilities. Here, the major focus was on the joint Franco-German "European Pressurized Water Reactor (EPR)" project. The activities relating to nuclear waste management are concentrated on the long-term safety of final repositories for high-active waste.

At the Jülich Research Center, the scope of the work related to incident-conditioned risks of large-scale nuclear systems was widened to include conventional plants, too. Nuclear safety research was targeted at the exhaustion of the potentials of passive, automatic safety systems, using available HTR know-how, to limit radio-toxic releases. The activities concerning nuclear waste management were concentrated on the safe interim and final storage of existing waste from high temperature and research reactors. They also comprised waste characterization and the development of associated methods and separation techniques.

At the Rossendorf, Dresden and Zittau sites (including the Rossendorf Research Center and the Rossendorf Association for Nuclear Process Engineering and Analysis (VKTA e.V.), the following experimental and theoretical work was carried out:

- material safety (radiation-induced embrittlement of reactor pressure vessels and their internals),
- analysis of light water reactor accidents (ATWS, reactivity- induced accidents, core meltdown accidents, hydrogen distribution and deflagration),
- thermofluid dynamics incl. development of two-phase measuring technique, structure-mechanical integrity analysis of LWR components,
- investigations relating to innovative reactor concepts,
- development of safeguards methods for internal core material monitoring,
- decommissioning, dismantling and disposal of the nuclear facilities existing at the Rossendorf Research Centre since 1957 and execution of further tasks in the field of environmental and radiation protection by the VKTA.

5.2.3 Reporting of R&D Activities under the AP

Under Article 2.a.i of the AP, the State has to report R&D activities not involving nuclear material carried out anywhere that are funded, specifically authorized or controlled by, or carried out on behalf of the State. Excluded from the reporting obligation are activities related to theoretical or basic scientific research, or in the field of final waste disposal, as long as the processing does nor include the separation of elements. Also excluded are R&D activities related to improved maintenance.

With respect to the declared will of the Federal Government to phase-out the use of nuclear energy for electricity production and the executed practice to terminate all governmental funding of R&D activities in this field, there will remain few activities to report under Article 2.a.i of the AP. Besides the maintenance of the existing plants, there is no government - supported initiative to develop new processes or systems.

An area where still fuel cycle related R&D activities are on-going is the URENCO case, where the State executes a control function within the Treaty of Almelo and where R&D activities are subject to reporting under Article 2a(i) for this reason.

6 Conclusion

After extensive activities in the nuclear field in the past, the Federal Republic of Germany has made the decision, and done concrete steps, to phase-out the use of nuclear energy for electricity production and to terminate all governmental funding of R&D activities in this field. An arrangement with the power utilities was achieved, paving the way for the gradual closing down of the currently operating nuclear power stations.

When preparing for the implementation of the Additional Protocol, we see this development reflected in a series of aspects:

- There exist many facilities and LOFs in different stages on their way of being decommissioned: shut down, closed down, under decommissioning, or already completely dismantled with the respective sites returned to ‘green meadow’ or devoted to non-nuclear uses. The exact status of these facilities and LOFs is relevant for treatment of these locations under the Protocol. The decommissioning is an ongoing process and will require a close follow-up in the coming years for the reporting under the AP.
- Research centres and industrial areas which in the past were mainly devoted to nuclear activities developed to diversified and multi-disciplinary research institutions with a wide range of different activities or to technology parks with only a small fraction of remaining nuclear activities. This has many impacts on the definition of the ‘site’ boundaries.
- As a result of the Federal Government’s decision to phase out the use of nuclear power, R&D activities which in the past covered nearly all areas of the fuel cycle, now primarily focus on safety aspects. The intention of R&D activities is to improve maintenance and safety. Besides the maintenance of the existing plants, there is no government - supported initiative to develop new processes or systems. There will remain only few activities to report under Article 2.a.i of the Protocol.

The German Government has decided to transfer the executive responsibility of the Additional Protocol to the European Commission as far as possible, and has established the legal instruments required to implement the Protocol in Germany. The Government, Euratom and the industry associations concerned undertake efforts, since several years, to inform the facility operators about and to support them in fulfilling their new obligations and thus to make sure that all parties involved are well prepared when the Additional enters into force in the European Community.

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Experience and current activities at the Institute of Isotopes, Budapest, related to nuclear safeguards and forensics

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Abstract: The report introduces the Institute of Isotopes and describes research and services related to nuclear safeguards and forensics. Available equipment and facilities are listed.

About the Institute

The Institute of Isotopes (IoI, or IKI in Hungarian) of the Hungarian Academy of Sciences, founded in 1959, is a research organization engaged in fundamental and applied research.

During the sixties and seventies research has been supplemented by practical activities addressing the needs of the growing field of radioisotope applications, such as the production of radioisotopes and the numerous industrial applications (fabrication and implementation of various measuring gauges, tracer studies, gamma irradiation services and design and fabrication of equipment and facilities). In the eighties about 400 employees were engaged in the Institute.

Starting from the early sixties the Institute developed its capability to produce radioactive substances and sealed sources mainly for domestic use covering about one half of the needs. Export of radioactive products increased gradually, reaching a 60% share of the total production in 2005, dispatching about 33 000 consignments of radioactive products. In 1993 the production of radioisotopes and most industrial applications were separated from the Institute forming the Institute of Isotopes Co. Ltd, a profit oriented company. The Company's total turnover was close to 10 million euro in 2005.

Associated Companies (formerly parts of the Institute)

- **Institute of Isotopes Co. Ltd. :** production of radioactive pharmaceuticals and sealed sources; providing facilities (hot cells, water ponds, etc.) for safe handling and transport of high activity radioactive sources
- **IZINTA Ltd. :** Commerce and transport of radioactive and other material

Main research areas (Reflecting more-or-less the organizational structure of the Institute)

- Radiation chemistry and dosimetry
- Nuclear data, gamma and neutron induced reactions
- Radioactive tracer techniques
- Catalytic reactions and surface chemistry
- Nuclear safeguards and forensics

Based on historical grounds the Institute has extensive experience with the measurement and handling of radioactive (including nuclear) material.

Technical assistance is provided upon request in the above research areas and in other nuclear related tasks, such as:

- Central registry of radioactive materials at national level *
- Evaluation of license applications for packaging and transport of radioactive material *
- Security of radioactive sources
- Safeguards verification of nuclear material
- Identification and characterization of illicit nuclear material *
- Studies of radiation resistance of materials and equipment

* these tasks have been delegated to the Institute by governmental decrees.

Historical highlights

Hungary signed the NPT in 1968; the first IAEA inspection was performed in 1972.

- 1972 the Initial Report was prepared by the IoI and submitted to IAEA
  - » (technical safeguards functions were delegated to IoI)
- 1975 γ-spectrometry was applied in safeguards
- 1980 Nuclear Underwater Telescope was developed and applied [Ref. 5]
  - » Identification, item counting and Cerenkov viewing of SFAs
- 1985 HRGS was developed for the verification of WWER-440 and MTR type fuel (intrinsic calibration) [Refs. 6,7,8]

- 1985 Development of nuclear isomer activation detectors [Refs. 9,10]
- 1990 Application of miscellaneous detectors [Refs. 10,11,12,13]
  - » (isomer activation, bubble, track-etch, Si-diode)
- 1995 Development and application of Spent Fuel Attribute Tester (SFAT) [Ref. 14]
- 2000 Studies of detection and identification of NM of unknown (illicit) origin

  » γ-spectrometry, neutron coincidence counting [Refs. 15,16,17,18]

  » Application of PGAA (prompt gamma activation analysis using the cold neutron beam at Budapest Research Reactor) [Ref.19]
- 2000 Assay of Pu-Be sources (determination of the "true" Pu content)

  » γ-spectrometry, neutron coincidence counting (validated by calorimetry provided by JRC IPSC, Ispra) [Refs. 20,21,22]
- 2002 Participation in the Round Robin exercise (characterization of HEU sample)

  Participation in field exercises following the ITWG's Model Action Plan
- 2005 Assay of damaged reactor fuel (initial inventory taking) [Ref. 23]

  » γ-spectrometry, neutron counting
- 2005 Implementation of mass spectrometry for the characterization of nuclear material and the analysis of environmental samples [Ref. 24]

Security of radioactive sources

Associated with its central role in the applications and transfer of all radioactive materials imported to or produced in Hungary the Institute maintains a computerized central **registry of radioactive sources** (including sealed sources and unsealed substances).

With respect to security and safe handling of radioactive sources the Institute, in collaboration with the Institute of Isotopes Co. Ltd., is assisting the Hungarian Atomic Energy Authority (HAEA) in the verification of inventories, and in the search, investigation and handling of seized and abandoned sources.

It is the Institute that provides expert opinion on packaging and special form of and special transport arrangements for radioactive material based on technical evaluation of applications to support the Hungarian Atomic Energy Authority in its licensing role.

Starting with safeguards

With respect to safeguards the Institute has been the contact organization to IAEA on technical issues since 1972 until the mid-nineties, including the maintenance of the nuclear material accountancy at national level and preparation of reports to the IAEA. Then the HAEA took over the accountancy task. Now the Institute is the **Technical Support Organization** (TSO) to the Hungarian Atomic Energy Authority. (Examples: Implementation of SFAT and verification of damaged fuel inventory at Paks NPP)

Response to illicit trafficking

The experts working in the R&D labs are also engaged in the practical aspects of nuclear forensics, i.e. the participation in the first response actions on the spot (incident site), and the characterization of seized nuclear material in the laboratory by γ and mass spectrometry.

Safeguards R&D

Safeguards R&D emerged from the experience related to the assay of radioactive (incl. nuclear) material, applied in the physical and chemical research carried out in the Institute.

R&D at the Institute (IoI) related to safeguards started in the seventies addressing the following **objectives**:

1. Satisfy domestic needs (e.g. Underwater Telescope used to identify, item count and verify spent fuel assemblies (SFAs) at Paks NPP)
2. Assist IAEA inspections (e.g. using SFAT) to verify SFAs at Paks NPP)
3. Explore novel methods for safeguards purposes (e.g. γ and n activation of nuclear isomers, quantitative assay of Pu content in Pu-Be neutron sources)

As a fundamental tool **γ-spectrometry** has been developed and applied for the verification and characterization of nuclear material in Hungary. Other techniques have also been applied as specific needs arose or investigated and developed as byproducts of basic research in nuclear physics or chemistry. The major research areas are briefly summarized below.

- *γ-spectrometry*

- SFAT for WWER-440 type SFAs developed and installed at Paks NPP (used by IAEA inspectors) [Ref. 14]
- gross and partial defect test methods for WWER and WWR-SM (research reactor) fresh and SFAs using NaI, HPGe and CdZnTe detectors [Refs. 6,7,8]
- assay (verification) of damaged spent fuel stored in sealed containers at Paks NPP, supported by neutron counting. See Fig.1 [Ref. 23]

Fig. 1: Underwater Verifier to be used for assay of damaged spent fuel at Paks NPP

- *γ-spectrometry and neutron-coincidence counting*

- quantitative measurement of plutonium content of Pu-Be neutron sources. See Fig. 2. [Refs. 20,21,22] It is noted that the Pu content of Soviet made PuBe neutron sources were not declared in the original certificates, the sources are accounted for by their nominal Pu weight being overestimated as compared to the real (measured) values.

Fig. 2: Neutron Collar used for Pu assay on Pu-Be neutron sources

- *Miscellaneous γ and n detectors*

- Silicon diode, isomer activation, track-etch, bubble for gross defect test and profile measurement on WWER SFAs [Refs. 10,11,12,13]

- *Mass spectrometry*: isotopic and elemental analysis of environmental samples (e.g. swipes, sediments) using high-resolution inductively-coupled-plasma sector-field mass spectrometer (ICP-SFMS Element 2, Thermo Electron Co.-Finnigan). See Fig. 3 [Ref. 24]

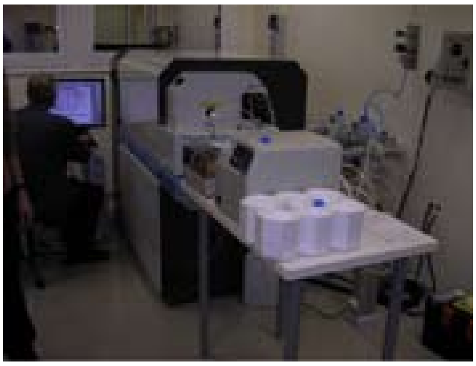

Fig. 3: ICP-SFMS Element2 with ARIDUS sample introduction unit

- *Underwater optical telescope* for spent fuel identification by serial number, item counting and verification by Cerenkov glow observation (R&D terminated) [Ref. 5]

R&D in nuclear forensics

In the mid-nineties the task of **identification, characterization and securing illicit nuclear material** seized in Hungary was delegated to the Institute (IoI) by governmental decree. The instrumentation and expertise used for safeguards purposes could also be applied in this field; however, new tasks were also formulated to address specific problems, such as the **mass spectrometric analysis** of materials involved.

Recent R&D activities:
- characterization of seized uranium samples by γ-spectrometry [Refs. 15,16,17]
- analysis of uranium sample (Round Robin) [Ref. 18]
- study of detectability with interfering radioactive sources and shielding
- assay of Pu in Pu-Be neutron sources [Refs. 20,21,22]
- assay of nuclear material by PGAA [Ref. 19]
- mass spectrometry for the analysis of nuclear material of unknown origin [Ref. 24]

The expert team of the Institute participated in the development of the national Action Plan for the joint response of all relevant authorities and institutions, and in a number of exercises simulating the seizure of illicit nuclear material. In 2002 our laboratory participated in the international “Round Robin” test on the characterization of HEU samples.

Forensic studies were based on the **γ-spectrometric** capabilities and expertise at the Institute. A novel method has recently been developed for the determination of the ‘age” of nuclear samples.

Recognizing the needs for more comprehensive characterization of illicit nuclear material the Institute extended its technical capabilities by implementing a high resolution **ICP-SFMS** mass spectrometer, which started operation in 2005. Sample preparation and measurement methods have been and are currently developed to characterize nuclear material, with respect to isotopics and trace elements. For environmental monitoring purposes the development focuses on long lived radioactive nuclides. In combination with ICP-SFMS laser ablation is applied to analyze solid samples directly. See Fig.4

Fig. 4: ICP-SFMS Element2 with Laser Ablation unit

It is worth mentioning that other research areas, such as **prompt gamma activation analysis** (PGAA) utilizing the cold neutron beam at the Budapest Research Reactor lead to some interesting new applications also in the field of nuclear forensics. The method is based on high energy prompt gamma detection, therefore a suspect package (shielded container) can be interrogated without opening to detect and characterize uranium content. See Fig. 5

Fig. 5: Cold neutron beam exit used for PGAA

Facilities, equipment

The R&D laboratories of the Institute are well equipped with basic instrumentation (gamma spectrometers, neutron coincidence counter, ICP-SFMS mass spectrometer), but some instruments have to be updated and/or upgraded. For example more efficient detectors, such as a high sensitivity well-type Ge detector is needed to increase measurement sensitivity.

Main Facilities, Equipment and laboratories related to nuclear research

- **Gamma spectrometry:** (HPGe, CdZnTe, NaI detectors, signal processing electronics, low background iron chamber). Used for safeguards verification and forensic measurements, such as isotopics and age attributes of nuclear material
- **Neutron (coincidence) counting:** (neutron collar, bubble and track-etch detectors). The collar was used for measuring Pu; small size neutron detectors were used to characterize spent fuel
- **Mass spectrometry** (ICP-SFMS), equipped with Laser Ablation Unit; installed in a clean laboratory. Used to measure isotopic and elemental composition of seized material
- **Cold neutron beam** equipped with HPGe triple coincidence detecting and beam chopper enabling simultaneous **PGAA**. Used to detect and categorize nuclear material in shielded package
- **Linear Electron Accelerator** (4 MeV LINAC). Used as a pulsed neutron source to study feasibility of nuclear material detection [Ref. 25]

- Chemical and thermoluminescence **dosimetry.** Used for the measurement of high gamma doses
- **SEM-EDX** (Scanning electron microscope with XRF probe). Used for the characterization of seized material
- At collaborating institutes (within the research campus): α-spectrometry, XRF (X-ray Fluorescence), PIXE (Particle Induced X-ray Emission), etc. are available
- **SFAT** installed at Paks NPP, for the verification of spent fuel and the absence of undeclared nuclear material
- **Underwater Verifier** (FORK type) for assay of damaged nuclear fuel at NPP

Supporting HAEA, IAEA, EURATOM

The above techniques and the R&D performed supported national authorities in the following practical task areas:

1) Safeguards (as technical support to HAEA)
 - Verification of WWER-440 SFAs and non-fuel items in the pond
 - Verification of WWR-SM (research reactor) fresh and spent fuel assemblies
 - Verification of Pu samples and Pu-Be neutron sources
 - Verification of damaged WWER-440 SF (broken fragments)
 - Characterization of SFAs (Burn-up distribution, neutron and γ fields, irradiation history)
 - Analysis of environmental (swipe, etc.) samples

2) Illicit trafficking (forensics)
 - Identification and first assessment of seized or found nuclear material on the spot
 - Detailed NDA and DA assay in laboratory to fully characterize nuclear material

Cooperation

Existing R&D co-operation with EU and IAEA

Hungarian support program to IAEA safeguards has continued for more than one decade. Examples: an SFAT developed by the Institute has been used by IAEA inspectors to verify low burnup and long cooled fuel assemblies at Paks NPP. The incident in Paks NPP in 2003, where a number of fuel assemblies were seriously damaged, created a technical safeguards problem. The verification of damaged assemblies can be done with techniques developed by researchers of the Institute. Measurement of Pu content in Pu-Be neutron sources enables the users to establish a realistic inventory.

The Institute established fruitful cooperation with JRC institutes. IPSC, Ispra provided us with a calorimeter by which the gamma/neutron Pu-Be measurement could be validated. With ITU a number of topics have been selected for cooperation, such as the joint analysis of seized nuclear material, laser ablation techniques, and the age determination of uranium bearing samples, as well as the development of the Model Action Plan for Hungary and in-field exercises (See Fig.6). IRMM provides us with necessary certified reference materials (CRMs)

Fig. 6: In-field exercise for identification and categorization of seized nuclear material

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Implementation of domestic regulation on small owners of nuclear materials in France

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Abstract

In France, a detailed and comprehensive regulatory system takes into account small owners of nuclear materials. The enforcement of the requirements stipulated by this system is first ensured by the centralization of the data submitted by operators and also by on-site inspections carried out by sworn and accredited inspectors under the competent authority. Inspections provide a global overview of the controls implemented by operators and an evaluation of the risks of theft or loss of nuclear materials.

The first part of the paper deals with the legal framework regarding the use of nuclear materials by small owners. Emphasis is put on the declaration, which must be prepared and submitted each year. The second part shows how this declaration may provide guidance to French authorities and inspecting bodies to control the proper application of regulatory requirements. A description of the various inspection phases is given .

1. Overview of the French regulations

France has developed a complete nuclear fuel cycle from mine to reprocessing plants, and is also a nuclear-weapon state, which has signed the Non Proliferation Treaty. Along with nuclear activities, small quantities of nuclear materials are also used, outside the nuclear fuel cycle, in particular in industrial, medical and research sectors.

Considering its nuclear situation and conscious of its national and international commitments in terms of national public security and nuclear non proliferation, the French government set up a national safeguard system under the authority of the Ministry in charge of Industry which ensures protection and control of nuclear materials.

This system is based on specific regulation which covers the entire civil nuclear field as well as the industrial, medical and research sectors. The basic aim of this regulation is to prevent or detect without delay the disappearance, loss, theft or diversion of nuclear materials, or equipment containing these materials regardless of their chemical or physical form.

The main text of this regulation, the Code of Defense, determines the current regulatory framework related to the protection and control of nuclear materials relying on three main principles:

1) Licenses are required for anyone desiring to undertake significant activities in the following fields: import, export, storage, use and transport of nuclear materials.
2) Operators are responsible for the implementation of nuclear materials physical protection, control and accountancy measures, under the control and inspection of the national Authority.
3) A penalty system is provided for in particular in case of non declaration of nuclear materials theft, loss or diversion.

The decree n° 81-512 of 12 May 1981 specifies the different types of nuclear materials concerned with the French regulations, which are fissile and fertile materials and those identified as likely to be used in

	Plutonium and ^{233}U	Uranium $\geq 20\%$ ^{235}U	Uranium $< 20\%$ ^{235}U	Natural and depleted uranium, thorium	Deuterium	Tritium	Lithium enriched in Lithium 6
Licensing	>3 g	>15 g ^{235}U	>250 g ^{235}U	>500 kg	>200 kg	>2 g	>1 kg ^{6}Li
Declaration	<3 g >1 g	<15 g ^{235}U >1 g ^{235}U	<250 g ^{235}U >1 g ^{235}U	<500 kg >1 kg	<200 kg >1 kg	<2 g >0,01 g	<1 kg ^{6}Li >1 g ^{6}Li
Exemption	<1 g	<1g ^{235}U	<1 g ^{235}U	<1 kg	<1 kg	<0,01 g	<1 g ^{6}Li

Table 1: categorisation of nuclear materials according to the decree of 12 May 1981

Type of nuclear materials	Uses	Fields
Depleted Uranium	Radiation shielding	• Industrial gamma radiography • Medical radiotherapy
	Balance weights	• Aeronautics • Oil-well drilling
Thorium	Welding electrodes	• Metallurgy
	Aircrafts alloys	• Air museums
	Chemical Products	• Suppliers of chemical products • Laboratories • Pharmaceutics
Natural Uranium	Chemical Products	• Suppliers of chemical products • Laboratories • Pharmaceutics
	Dye for crystals	• Crystal manufactures
Deuterium	Solvents	• Laboratories, NMR (Nuclear Magnetic Resonance) techniques
Tritium	Radio luminescent devices	• Aeronautics • Watch manufactures
	Radiotracer	• Hospital • Laboratories
Highly enriched uranium Plutonium	Sources	• Source users

Table 2 : application fields of nuclear materials owned by declarants

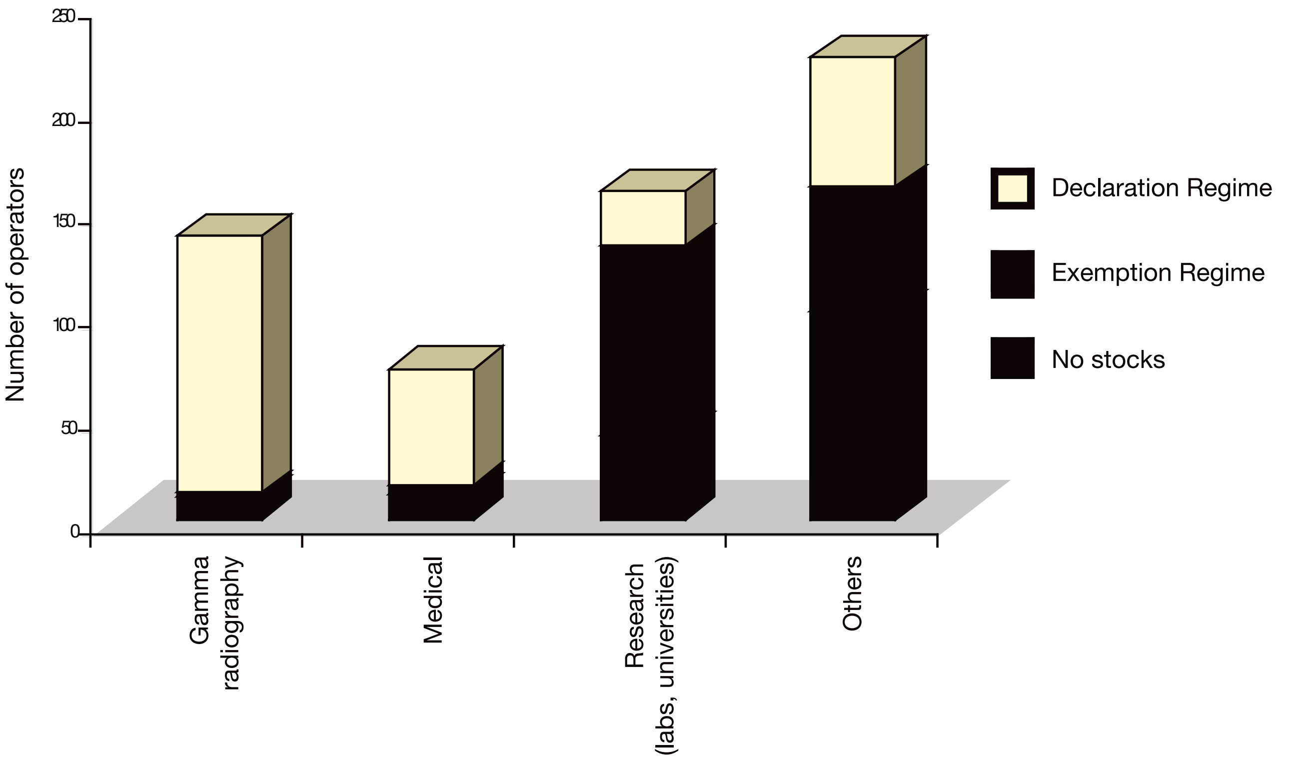

Figure 1: status of operators subject to declarations regrouped by activity fields on 31 Dec. 2004. The category "No stocks" corresponds to operators who declared not to be in possession of any kind of nuclear materials.

the confection of a nuclear weapon. They are listed as : plutonium, enriched uranium with 20% or more of uranium 235, enriched uranium with less than 20% of uranium 235, natural and depleted uranium, thorium, tritium, deuterium, and lithium enriched in lithium 6.

This decree also establishes three regulatory regimes, based on the nature and quantity of the nuclear materials involved, as presented in Table 1.

1) Licensing: for significant quantities of nuclear materials, a licence from the Ministry of Industry is required.
2) Declaration: below defined quantity thresholds of held nuclear materials, no preliminary licence is required but a simple annual declaration of undertaken activities.
3) Exemption: no specific requirements for the operator but the quantities of nuclear materials held must be very limited.

In France, operators under the declaration regime are called « declarants »

Finally, orders complete the legal framework. In particular, the order of 14 March 1984 stipulates technical arrangements related to the control, the accounting and the physical protection of nuclear materials under the declaration regime. It was modified on 21 May 2003 to specify the rules to be followed regarding supporting documents justifying inventory changes and inventory taking.. A revision of these texts is programmed in the next year but no significant change is to be expected regarding the obligations of declarants.

It is worth noting that in France, safety and radiation protection are subject to specific regulations and authorities. These regulations also apply to most of nuclear materials, except Deuterium and Lithium that are not radioactive.

2. Activities of declarants

Declarants activities concern the medical, industrial, research fields and, in some rare cases, artistic uses. These activities are described in detail in the table 2, below, for each type of nuclear materials. One can notice the diversity of uses of nuclear materials in non-nuclear fields.

Annual declarations, as described below in section 3, provide precise figures on the inventory of nuclear materials held by the “small owners” population, which gathers French operators under the declaration and the exemption regime. Figure 1 provides an overview of this population regrouped by activity fields based on declarations of year 2004. At the end of year 2004, about 270 declarants were identified in France and about 160 operators holding nuclear materials under the exemption regime. Industrial radiography and medical radiotherapy users represent the highest population of operators placed under the declaration regime (more than 65%). On the contrary, the majority of operators working in the research field belong to the “exemption regime” category as most of them are in possession of small quantities of chemical products such as uranyl or thorium oxides, acetate or nitrate used for analyses or deuterated solvents used in Nuclear Magnetic Resonance techniques.

As shown in Figure 2, depleted uranium represents the main nuclear materials held by small owners (94.25% of the whole nuclear materials stock). The

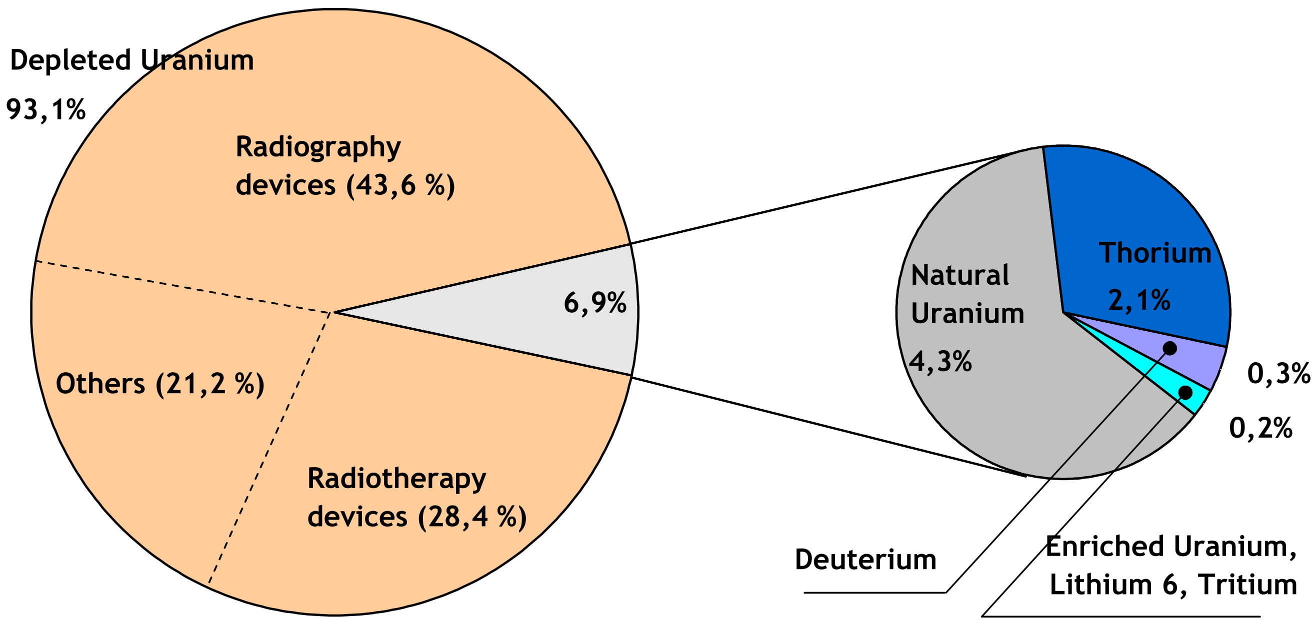

Figure 2: mass distribution of nuclear materials held by declarants (ref. Declaration of 31 Dec. 2004)

declared inventory in thorium and natural uranium is much less significant. Other nuclear materials only have a negligible part in the inventory held by declarants. Most of the depleted uranium held by declarants is actually encountered among industrial radiography or radiotherapy users. These materials are given the highest priority in terms of control by the Authority.

3. Regulatory requirements related to the declaration regime

Prior to the receipt of nuclear materials under declaration regime, concerned operators must establish an initial declaration. This declaration, which is to be sent to the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), acting as technical support body for the competent authority, includes the following data:

- Identification data (company's name, address,…) and the name of its owner and operator who are legally responsible;
- Type of activities concerned and localization of nuclear materials.
- Description of nuclear materials protection measures

After this initial declaration, the operator must send to IRSN, every year before January 31 the following data:

- Inventory of nuclear materials as of December, 31st of the previous year;
- Inventory changes occurred during the previous year, including the identification of shippers and recipients;
- Maximum inventory of nuclear materials and inventory changes expected for the present year.

Inventory data must be provided for each category of nuclear materials defined in table 1.

Declarants must also set up a local accounting system based on an accounting ledger. This ledger gathers chronological records of the various types of inventory changes that occur at the facility including production, consumption, reception or shipment of nuclear materials. The type of book to be used is not stipulated in the regulation. A paper copybook or a computerized system can both comply with this requirement, as long as it can be proven tamper proof.

The operator must keep records of all supporting documents dealing with transactions involving nuclear materials as justifications of the inventory changes, for at least five years.

Before filling in the annual declaration, the operator must carry out a physical inventory to ensure that all nuclear materials present in the facility are correctly listed in the accounting system.

It is also recommended that the operator periodically check the presence of the nuclear materials at their expected location, especially when the device containing the materials is not used frequently.

Finally, the declaration also has to describe the main features concerning facility layout related to surveillance and physical protection of materials. These features must be adapted to the use and the attractiveness of nuclear materials. Regarding physical protection requirements, the Authority has admitted that nuclear materials should be kept at least under lock and key, and keys should be accessible to authorized personnel only. Alarm and guards are not mandatory, but in some special cases, the Authority has required an alarm system.

4. Enforcement of the declaration regime requirements

As previously mentioned, IRSN acts as the technical support body of the national Authority of the represented by the Ministry in charge of Industry. Its missions include centralization of all declarations on nuclear materials, especially those submitted by owners of small quantities of nuclear materials.

Every year, a declaration form is sent by IRSN to operators formerly identified as holding nuclear materials without having a licence from the Minister in charge of Industry. This form is drawn up on an evolutionary basis and can be changed based on experience and control objectives. The detection of new owners is ensured by investigations by IRSN but also by the commitment of licensed companies. Indeed, companies under the licensing regime have to declare on a daily basis any change occurring in their nuclear materials inventory. This includes all transfers of nuclear materials, for which the identity of companies sending or receiving the nuclear materials has to be specified. In the same way, the information made available in annual declarations by declarants is used to detect new or unknown owners of nuclear materials.

IRSN is also in charge of evaluating the declarations returned by declarants. This evaluation consists of carrying out consistency checks with the previous declarations and making crosschecks and comparisons between the information transmitted by other declarants or submitted by licensed companies.

Declarants, whose declared nuclear material inventory approaches or exceeds the limits corresponding to the licensing regime, are identified. Those submitting declaration forms containing missing, suspicious or non-reliable information are contacted and asked for new declarations comprising necessary corrections. The analysis of such cases can lead to on-site inspections if necessary.

If a declaration ever mentions the loss of nuclear materials, it is assigned the highest priority in the analysis and results in informing immediately the Ministry in charge of Industry. Once checked, the data is processed into the centralized national accounting database managed by IRSN. This database contains also up-to-date general information related to the company, including its name and address, its field of activity, the names and phone numbers of the persons legally responsible or appointed as main interlocutor for questions referring to the nuclear materials declared. It contains the data taken from every annual declaration related to the quantity and nature of the nuclear materials.

Data centralization within the IRSN database represents a useful tool as it implies systematic and efficient check of annual declarations and makes possible rapid detection of irregularities and problematic cases. The national database is used to provide any information required by the Ministry in charge of Industry. Besides, it is a useful support to provide data in view of on-site inspections.

5. On-site inspections

On-site inspections are carried out by sworn and accredited inspectors under the authority of the Ministry in charge of Industry. They are also a pertinent tool in enforcing the declaration regime requirements. Inspection programs are established after the analysis of annual declarations but also on the basis of specific events pertinent to a declarant or to a field of activities. IRSN is also involved in the technology watch of fields concerned by the use of nuclear materials, which can also lead to on-site inspections. These actions allow inspectors to carry out more than 35 inspections per year at declarants facilities.

The main points of an inspection are:

- to remind the declarant of the national regulation related to control and protection of nuclear materials;
- to remind the declarant of the links between this regulation and others concerning radioprotection or radioactive source management (if needed);
- to check the compliance with the regulation and particularly with Order of 14 March 1984. In particular, inspections allow to evaluate the local nuclear materials accounting system implemented by the declarant;
- to check the documents related to these requirements;
- to check the correctness and the completeness of the previous physical inventory (portable detection devices adapted to the nature and the quantity of radioactive materials are used);
- to analyse the arrangements made by the operator to ensure the physical protection of nuclear materials.

After the completion of an inspection, inspectors send a report to the competent authority, suggesting, if needed, corrective actions to be undertaken by the operators.

More than 300 on-site inspections carried out since 1995 have provided DEND with a sound knowledge of the use of nuclear materials held by small owners in France. This allows IRSN to play a main role in the preparation and the implementation of the regulatory documents concerning the use of nuclear materials in the medical, industrial or research sectors on behalf of the Authority. It also allows IRSN to identify specific issues and raise the attention of the Authority whenever necessary.

During the past years, the few losses in nuclear materials that occurred were due to the lack of knowledge of declarants concerning nuclear material management. Most of the time, unused or damaged devices were involved.

Concerning the rare thefts that have involved small quantities of depleted uranium, most of them have taken place due to a lack of surveillance, even for very short periods, of vehicles transporting industrial gammagraphy equipment. In all cases, the motive was the attractiveness of the vehicle rather than the nuclear materials themselves.

6. Conclusions

In France, a detailed and comprehensive regulatory system has been set up for small owners of nuclear materials. The enforcement of the requirements stipulated by this system is first ensured by the centralization of the data submitted by operators and also by on-site inspections carried out by sworn and accredited inspectors under the authority of the Ministry of Industry. Inspections provide a global overview of the controls implemented by operators and an evaluation of the risks of theft or loss of the nuclear materials held in the facilities. Experience has shown that, even though the materials possessed by small owners have a low sensitivity in terms of nuclear proliferation, they can have a strong impact through the media. IRSN actions contribute to a better understanding of the regulatory requirements by operators and offer the French Authority the guarantee that the control practices of operators are consistent with the regulatory framework. Setting up such measure participate in promoting and improving the security culture.

Aspects of Safeguards Application in Lithuania

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Abstract: Changing Safeguards environment has been a phenomenon in Lithuania since the Agreement between the Government of the Republic of Lithuania and the International Atomic Energy Agency for the Application of Safeguards in connection with the Treaty on the Non-proliferation of Nuclear Weapons (Safeguards Agreement) was signed in 1992.

Safeguards was a new matter in Lithuania back then and its perception was not a one day work. Development of the national system of accounting for and control of nuclear material took years. Safeguards implementation in Lithuania was not a simple and easy task for the IAEA either. The Ignalina Nuclear Power Plant inherited by Lithuania from the Soviet Union brought its particularity as there was no precedent experience in safeguarding the RBMK type reactors.

In March 1998 Lithuania signed the Additional Protocol to its Safeguards Agreement. After two years it was ratified and came into force on 5 July 2000. That was a certain change and a new stage of Safeguards application in Lithuania.

On May 1 2004 Lithuania together with 9 more countries became a member of the European Union (EU) and at the same time of the European Atomic Energy Community (Euratom). From the nuclear safeguards application in Lithuania point of you that meant the following changes: start of the Euratom safeguards application and shift from the bilateral safeguards agreement with the International Atomic Energy Agency (IAEA) to the trilateral one between the EU non-nuclear weapon states, Euratom and the IAEA.

This paper is aimed to briefly review developments, which took place through the course of safeguards application in Lithuania.

1. Introduction

Lithuania declared its independence in March 1990 and in August 1991 after the formal collapse of the Soviet Union the Ignalina NPP came under the authority of the Republic of Lithuania. The inherited nuclear power plant became the only facility of the nuclear fuel cycle in the country. However, the Ignalina NPP containing two units with RBMK type reactors was the outstanding installation bringing many new issues to be addressed by the young state. One of them was safeguards.

Back in early 1990s there was no experience in the safeguards application field from the Lithuanian side. Safeguards as the international verification regime was not exercised in Lithuania during the soviet times. Therefore, developing national infrastructure including legal and administrative issues was evolving process, which took several years. Safeguards implementation at the facility level had to be started from scratch too. The situation was even more peculiar because of the fact that the International Atomic Energy Agency (IAEA) had no previous experience in implementing safeguards at the nuclear power plant with the RBMK type reactors. However, during the following years the Ignalina NPP, considered as the black box in the beginning, was transformed by the effort of the IAEA inspectors, national authority staff and the facility personnel into the well-safeguarded and transparent installation.

Changes on the international safeguards arena with the appearance of strengthened safeguards had the influence on the safeguards application in Lithuania as our country was among the first ones to sign the Additional Protocol and bring it into force. Preparations and implementation of the Additional Protocol provisions was a next stage of safeguards application in Lithuania.

The big achievement for Lithuania became a membership in the EU. However, that meant certain changes in the nuclear sector. Lithuania was obliged to close down the Ignalina NPP and the time schedule was set for that. Membership in the EU indispensably affected the safeguards matters as well. Lithuania by joining the EU adhered to the Euratom Treaty. The IAEA safeguards along with the Euratom safeguards and interconnection between them has become a new feature of safeguards application in Lithuania.

2. State Nuclear Power Safety Inspectorate (VATESI)

Following the Government's resolution of 18 October 1991, the State Nuclear Power Safety Inspectorate

(VATESI) was established on 1 November 1991. The regulatory control of the Ignalina NPP and regulation of nuclear safety in general and radiation protection in the sphere of nuclear energy utilization was assigned to it.

After the Safeguards agreement was signed, establishment of the State System of Accounting for and Control (SSAC) of nuclear material was entrusted to VATESI too. Nuclear Material Control Division within VATESI was organized and made responsible for maintaining the SSAC.

Current VATESI structure is shown below.

3. Ignalina NPP

The Ignalina NPP was the only nuclear facility in Lithuania when the Safeguards Agreement was signed. The nuclear material accounting system at the facility level was rearranged to conform to the requirements of the Safeguards Agreement. Key Measurement Points (KMP) were set for the nuclear fuel physical inventory determination and flow.

KMP-A is the fresh fuel storage. From there the fuel is transferred to units 1 and 2, respectively KMP B and KMP F. KMPs C and G are the reactors. After discharge from the reactor, each fuel assembly is stored in a water pond (KMPs D and H) for at least one year for cooling. If fuel was not burned fully, the fuel assembly can be returned to the reactor. Therefore during the negotiations of the Facility Attachment it was agreed that the nuclear loss and nuclear production is reported after the fuel assembly is cut into two halves (upper and lower segments) and when it can not be used in the reactor anymore. Cut fuel is placed into a basket, which stores 102 pieces (51 assemblies). Full baskets are stored in the water pond area for cut fuel, respectively KMP E and KMP I for units 1 and 2. For the nuclear fuel flow, the KMPs are for: receipt (KMP 1); the nuclear loss (uranium burn-up) and the nuclear production (KMP-2); shipment from the facility (KMP-3); and accidental gain/ loss, exemption and de-exemption (KMP-4).

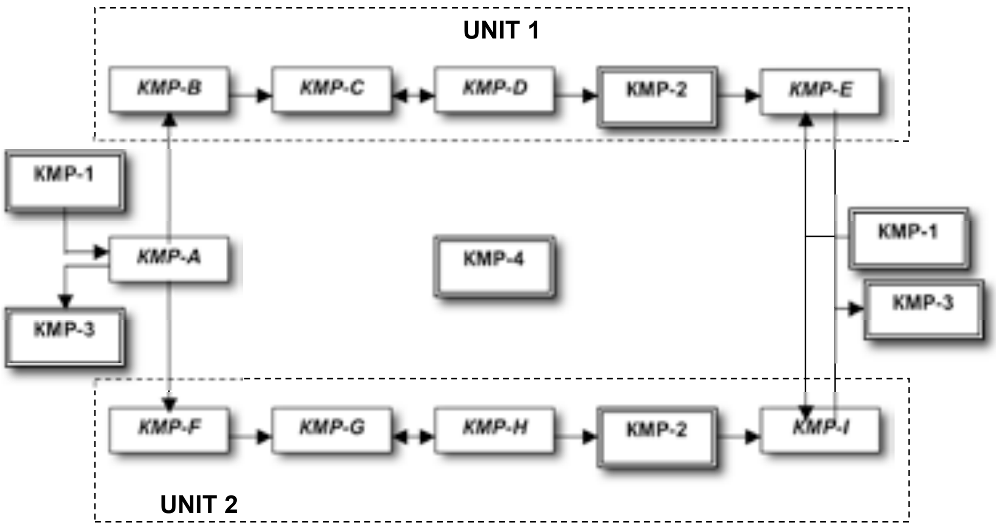


Fig. 1: Structure of the Ignalina NPP material balance area.

4. Dry storage

When the dry storage came into operation in 1999, it became a third material balance area in Lithuania. Before that the Ignalina NPP and the rest of territory were the only two material balance areas. Structure of the spent nuclear fuel dry storage material balance area is shown below.

KMP B is the real storage itself. KMPs 1, 2 and 3 are set for the determination of nuclear material flow.

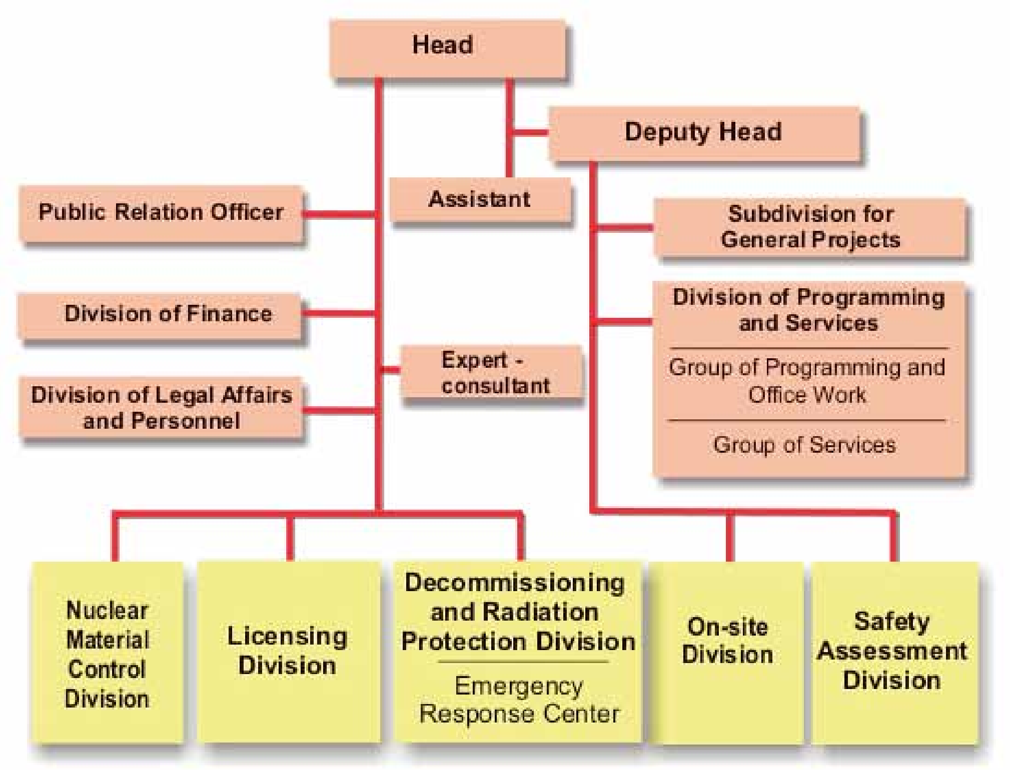
In the process of preparation to ship the spent fuel to the dry storage, the basket with cut fuel assemblies is placed inside a container. Two types of containers, CASTOR RBMK-1500 and CONSTOR RBMK-1500, have been used. The loaded CONSTOR container from the spent fuel pond in the unit was not shipped directly to the dry storage but, first, transferred to the welding area. It is KMP A in the accounting scheme.

5. Towards Integrated Safeguards in Lithuania

The cornerstones of IAEA safeguards application in Lithuania are the Safeguards agreement and its Additional Protocol. The latter was signed on 11 March 1998, ratified two years later and finally came into force on 5 July 2000.

In the beginning of 2001 VATESI submitted the initial declaration of Lithuania pursuant to the Additional Protocol requirements and renews it annually. In the Safeguards Implementation Report (SIR) for 2003 the IAEA stated that for 19 States the Agency found no indication of diversion of nuclear material or of undeclared nuclear material or activities. Lithuania was among those 19 States and the positive conclusion for our country was drawn for the first time. It was reiterated in the SIR for the consecutive years too.

The positive conclusion paves the way for the integrated safeguards implementation in the State. Discussion between the IAEA, State and operator on implementation of a short notice or unannounced inspections, provision of near-real time information on nuclear material flow to the IAEA has already been going on for several years, however, development of the integrated safeguards approach has protracted. It is has been influenced by the current situation when the first unit of Ignalina NPP has been closed down and new projects and processes related to the nuclear fuel use and storage are foreseen and implemented. It would be easier to develop and implement the approach for a stable and steady situation. However, the transfer of not fully burned fuel assemblies from unit 1 for reuse in unit 2 will take place. This is a completely new activity over power plant's operation time. The existing dry storage has been filled in and the transfers of spent fuel has ceased for some time. However, the new dry storage will be commissioned in a few years time and the transfers will resume. The integrated safeguards approach has to embrace all current and future activities, as the aim is to have the approach applicable for a long term.



Current VATESI structure

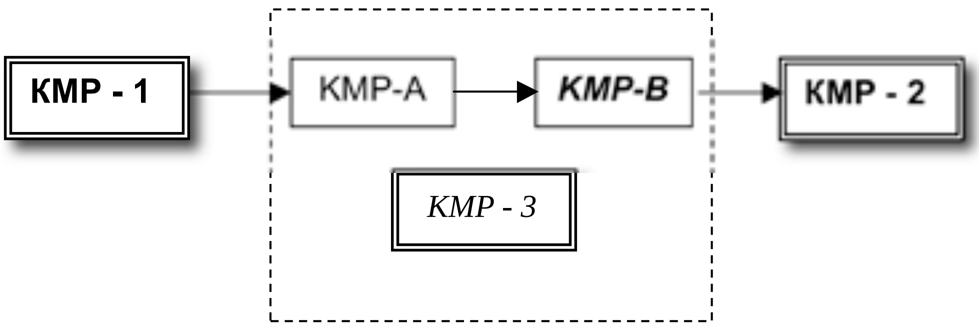


Fig. 2: Structure of the spent nuclear fuel dry storage material balance area.

6. Euratom Safeguards in Lithuania

Lithuania became a member of the EU on 1 May 2004. Treaty of Accession of the Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Slovenia and Slovakia signed in Athens on 16 April 2003 contained Protocol No. 4 on the Ignalina nuclear power plant in Lithuania. Article 1 of the protocol stated that Lithuania commits to the closure of unit 1 of the Ignalina NPP before 2005 and of unit 2 of this plant by 31 December 2009 at the latest. Lithuania has already fulfilled the first part of the commitment by closing down unit 1 on 31 December 2004.

The first DG TREN Directorate I inspectors' visit to Lithuania occurred yet prior to the accession. During the IAEA inspection in March 2004 at the Ignalina NPP, Euratom inspectors attended as observers. The independent inspection by DG TREN Directorate I took place already at the end of May 2004. Euratom inspectors came to verify the basic technical characteristics provided by the Ignalina NPP. The subsequent Euratom inspections took place together with the scheduled IAEA inspections. Euratom inspectors were present during the IAEA annual physical inventory inspection at the Ignalina in 2005 and 2006.

7. IAEA and Euratom safeguards conjunction

After Lithuania joined the EU, it became necessary to suspend the bilateral agreement with the IAEA on application of safeguards and its additional protocol, and adhere to relevant documents between the IAEA, Euratom, and the EU non-nuclear weapon states. This was not a quite new situation as it happened during the previous EU enlargements and the last time in 1995 when Austria, Finland and Sweden joined in. The only and main difference was the Additional Protocol. The strengthened safeguards system and its tool, the Additional Protocol, was under development then yet.

Lithuania already had four years of experience in implementing the Additional Protocol prior to joining the EU. Additional Protocol in the EU came into force at the end of April 2004 just before the enlargement. The IAEA took a position that changing from the bilateral additional protocol to the trilateral would not constitute a step back. Evaluation and drawing of conclusion under the additional protocol is done for states individually. Therefore, there would be no meaning to start everything from the very beginning especially as the positive conclusion for Lithuania was already drawn.

8. Conclusions

Starting from 1 May 2004, Euratom safeguards applied by the European Commission complemented the IAEA safeguards in Lithuania. Interconnection between the two safeguards systems stipulated in the trilateral arrangement between the IAEA, Euratom and the EU non-nuclear weapon states has not come into effect in Lithuania during the first two years of the membership. The prolonged transition has had no influence for the implementation of the IAEA safeguards in Lithuania and the integrated safeguards should be implemented in Lithuania in the nearest future.

Technical Sheets

Statistical Methods in Nuclear Materials Accountancy and Auditing

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1. Introduction

Statistical methods have wide applications in manufacturing of every kind, and nuclear manufacturing is no exception. Here, however, we are only discussing the particular uses of statistical methods which, in the last 50 years, have grown up around nuclear materials (NM) accountancy and auditing. This accountancy is concerned with ensuring that the **location** of all NM is accurately known and, in particular, to ensure that the **amount** of NM in each location is accurately known. The statistical nature of nuclear accountancy comes from the fact that the measurement of any quantity of material will incorporate the intrinsic measurement variation of the methods being used. For this reason, statistical modelling of measurement methods has always been an intrinsic part of NM accountancy.

The willingness to pay the cost of applying sophisticated statistical methods in NM accountancy reflects the hazards associated with misuse of the material. Every State having nuclear activities has legislation designed to ensure that the nuclear material on their territory is protected and that the material is only used for approved purposes. Concern to prevent proliferation of nuclear weapons led to the Euratom Treaty and to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and the consequent auditing of NM accountancy by international inspectors, including those from the International Atomic Energy Agency (IAEA). Thus, sampling theory applied to inventories of nuclear material has also become part of the statistical methods employed.

The existence of these "State Systems of Accountancy and Control of NM", and NPT-related international "safeguards" systems for supervision of accountancy, means that the management of nuclear facilities must give a certain priority to accountancy needs. Facility management wishes to have a state of the art accounting process for technical and economic reasons, but also to meet the requirements of national laws and international agreements. The task of facility management is to put in place the necessary procedures and technical means to ensure that a high level of accountancy is achieved. The basic processes that determine the quality of accounting information in any facility are:

- a **measurement system** that provides an accurate quantification of stocks and transfers of material;
- operating **records** that document material movements, material locations, identities of items and provide links to related measurement data; and
- accountancy **control procedures,** whereby information is regularly crosschecked against other information to detect inconsistencies and identify human errors.

Note that, in principle, accountancy anomalies could be due to unidentified measurement problems, or to human errors in executing procedures, or to falsification.

Statistical methods are a set of tools that are of relevance to the accountancy objectives of international safeguards organisations, of facility management, and of state agencies responsible for supervision. Each of these users will make use of the particular tools that are relevant to their particular goals. Here, however, we will limit ourselves to describing some of the generic questions where statistical methods have a role to play.

2. The application of statistics

Statistical Modelling of Measurement Methods: The statistical modelling of measurement results includes modelling of sampling and analysis errors in the use of destructive analysis methods, errors in non-destructive methods based on neutron interrogation, gamma emission and calorimetry as well as errors in accountancy tank volume and concentration measurements for reprocessing facilities. This modelling covers more than attributing a standard deviation to each measured value. It also includes knowing the covariances between measurements in as far as they may affect the detection of accountancy anomalies. A "measurement control programme" is necessary to ensure that real measurement performance during operating activities remains consistent with the statistical model that will be used for making decisions about anomalies. Statistical modelling is needed in order to define exactly how to monitor the performance of any measurement system. Models of measurement methods are validated by appropriate experimental studies, which quantify the parameters of the models. Such studies are often part of the method development, but this source of information is often supplemented by measurement intercomparison experiments in which different users of the method compare their performance.

Accountancy System Design: Any discrepancies between accounting values and "true values" should be sufficiently small that the accounting system is fit for purpose. This requirement determines the permitted uncertainty on measurements that are undertaken for the accountancy. The precision is ensured by having the appropriate measurement method, by having qualified measurement procedures and by monitoring the correct execution of these procedures. Given the existence of intrinsic measurement errors, there will always be some small amount of material that could go missing without the loss being detected. The question is, whether the missing amount of material is significant. What is a significant amount of material is defined by the objectives set by the state and/or by international agreements. Any accountancy system should be technically capable of detecting the loss of a significant amount of material. If quantitative accounting objectives are defined in terms of specification of a significant amount, this will generate requirements as regards the required precision of the facility measurement system. It will also generate requirements for the control of human errors affecting accountancy discrepancies. In examining these questions, statistical methods can help to identify the measurement system requirements at the design stage.

Accountancy Control Procedures: The most important accountancy control procedure is to verify the overall consistency of the present stock against previous records of receipts and shipments. This is the famous material balance equation designed to check "material unaccounted for". For any balance period, the material unaccounted for (MUF) is computed from the facility information as:

$$\text{MUF} = \text{Ending Inventory} + \text{Shipments} \\ - \text{Receipts} - \text{Beginning Inventory}$$

Each term on the right hand side is the sum of the measured masses of the corresponding nuclear material. The measurement of any amount, however, will incorporate the intrinsic measurement uncertainties of the methods being used to measure the material. If all the procedures related to accounting were carried out correctly, this material balance amount (MUF) should be just an accumulation of legitimate facility measurement errors. This means however, that a material balance is not obliged to be zero, even if the accounting activities have been carried out perfectly. As a result, one important control procedure is to ensure that the MUF for any balance period is acceptably small whilst taking account of the legitimate measurement uncertainties of the NM that has been processed. In principle, this is done by computing a standard deviation for the balance (denoted- σ_{MUF}) and judging the magnitude of the MUF value relative to this standard deviation. The standard deviation is usually computed on the hypothesis that the discrepancies (between accountancy value and true value) are caused only by legitimate measurement error. Hence, the computation of standard deviation is done using the material processing information for the balance period and knowledge of the measurement uncertainties of the facility measurement methods. This balance test is a control procedure for facility management but it is also an important auditing criterion.

The quality of the facility measurement system will determine the magnitude of the MUF standard deviation. Hence, the facility measurement system will determine the ability to detect the effect of anomalies that contribute to the value of MUF. Performance may appear satisfactory, in the sense that there are no anomalies given the standard deviations associated with the existing measurement systems. This, however, may be unsatisfactory in the sense that the standard deviations may be so big that unacceptable discrepancies may be undetectable. This emphasises the idea that there has to be some link between the precision of the facility measurement system and what is considered a significant amount of material from the point of view of the goals of state legislation or an international treaty.

Verification of Material Control: The verification being discussed here is essentially the verification that all material is accounted for. This is done by:

- checking the material balance - as described earlier;
- checking the consistency of accounts and operating records; and
- verifying the conformity between accounts and reality.

Checking the material balance is a task which an external auditor will usually carry out, even if it has been done already by the facility as an internal accountancy control. The second of these tasks, checking the consistency and correct use of operating records (from data creation through data processing, up to the accountancy reports), provides an additional input for assessing the ultimate reliability of accountancy declarations. It provides additional information, because it is possible for data processing errors to produce anomalies (affecting MUF value or the discrepancies in item declarations) that are small and undetectable within the given measurement error uncertainty. Absence of such data processing errors suggests that anomalies caused by human error are infrequent, and hence increases the credibility of the accountancy system. This enhancement of credibility is valid if anomalies are caused by human errors and if the hypothesis of falsification can be excluded. However, even if the hypothesis of falsification is not excluded, checking the consistency of operating records has the advantage that it increases the probability of detecting some falsifications, if they exist. Checking of operating records is designed in terms of random sampling of the process of record creation and subsequent use in data processing. This task is essentially one of tracing and reconciliation of source documents, computer files and data processing.

Verifying conformity between accounts and reality includes independently measuring selected material and comparing the results with the accounting values of the facility. This, of course, means that the auditor will also employ measurement methods that require statistical modelling. Sampling approaches to verify conformity with reality are designed using the inventory of material as the sampling frame. From the point of view of statistical theory, the planning of an audit for "conformity with reality" is concerned with choosing the sampling and measurement approach for verification. This means deciding how many items should be subjected to verification measurement and what should be the precision of the auditor's measurements for different sets of items. The specific objectives are expressed in terms of a desired probability of detecting undesirable anomaly scenarios (if they exist), while having limited false alarms (when anomalies are absent) and respecting auditor resource constraints.

There is a difference between the auditing perspective of facility management and that of an IAEA inspector. Auditing by the IAEA is designed to be able to detect "diversion" of any amount of material that has significance in terms of nuclear weapons development or production. At the level of the analysis **for designing** IAEA verification approaches, the State is treated as a potential adversary. The intensity of IAEA audit is determined by what kind of anomalies might cover the loss of a significant amount of material. One consequence of adopting such technical criteria is that an exhaustive verification of reality is required at every audit. This is because the sampling plan must provide the desired detection sensitivity for the falsification strategy that would be most difficult to detect. The perspective of facility management on the other hand is to get information about the incidence of measurement problems and human errors. This means that the sampling plan can focus resources particularly on those areas where management feels assessment of performance may be vulnerable to errors. Vulnerability can be related to new technology, personnel changes, etc. For management, auditing can be a searchlight whose focus of attention changes from one audit to the next. In either situation, part of the role of statistics is to optimize inspector resource allocation by deciding the audit intensity to be applied in order to achieve audit goals at reasonable cost.

Analysis of Accountancy and Audit Data: Once an audit has been carried out, the problem then becomes that of analyzing and interpreting the measurement results. Statistical methods for this include applying the estimation and tests needed to recognise anomalies, to assess the adequacy of material control and to assess the performance of the accounting process. For items that have been remeasured, anomalous discrepancies can be recognised by a test of the difference between the accountancy declared value and the auditor measured value. The recognition is a technical fact whereas the interpretation may depend upon the auditing perspective. Here again, there may be differences between the facility management perspective and an IAEA perspective.

The remeasurement of a random sample of items allows the auditor to estimate the total accounting discrepancy (L_{MUF}) in a material balance. This estimator of L_{MUF} is called the "D statistic" and can be used to provide an estimator of the true material balance (MUF_T). The estimator is always of the form MUF-D. This estimator is unbiased no matter what is the cause of the discrepancies. It is unbiased even if the discrepancies are the result of falsification or human error. For using MUF-D in this way, the statistical approach uses finite population sampling theory. Only the population sampling variation and the inspector measurement error enter into the variance of MUF-D. In addition, and again independent of the cause of the discrepancies, the estimator of the variance of MUF-D is also unbiased. Note that the variance of MUF-D is estimated taking account of the fact that all facility information may be false. Even in such a situation, the estimation method is valid. All of this is relevant to IAEA objectives where the auditor does not wish to exclude that discrepancies might be deliberate falsifications.

It is possible to analyse the effect of hypothetical falsification strategies on the material balance. This analysis characterises malfactor strategies in terms of "diversion into MUF" and "diversion into discrepancies". This shows that verification of material control must include testing the material balance estimator and verifying the declared values on randomly selected items. We also see that the required sensitivity of measurement for detecting anomalies will create requirements for both the inspector measurement system and the facility measurement system.

Statistical analysis for IAEA objectives has to treat accounting discrepancies as if they could be falsifications. From a management point of view, however, discrepancies may be considered as random variables whose probability distribution is the combined effect of intrinsic measurement errors and inadvertent human errors. Accountancy performance can then be defined as some measure of the combined effect of these factors on the material balance. One measure of performance is the mean square error of the total accounting discrepancy. Given that random samples of items have been remeasured, the mean square error of L_{MUF} can always be estimated. Statistical methods can then be used to test the consistency between the observed performance results from the audit and some desired quality targets. The desired quality targets express what management feels should be achieved by the facility measurement system and by control of human error.

3. Conclusion

As applied in international safeguards, statistical methods provide a methodology whereby verification of accounts can provide assurance that all nuclear material is accounted for. The methodology cannot of course give a logical proof that this is so. Instead, it allows the inspector to formulate a verification plan such that, if a significant quantity were missing from the accounts, the inspector has the desired probability of detecting at least one anomaly via his verification. This is called an adequate verification plan. The fact that the inspector carries out an adequate verification plan, and the fact that the result is that no anomalies are found, provides the assurance. In other words, assurance is provided when the inspector looks assiduously for the anomalies that would be the consequences of inadequate material control and reaches the final audit result that no anomalies are found.

Experience of this kind of verification has shown that it can only be efficient when the facilities have an accountancy system in which anomalies due to inadvertent human error are unlikely. This has given an impetus to ensuring that all facilities achieve best practise in the design and operation of their accountancy activities. The desire to ensure this by auditing the design of the accountancy system is one of the elements in the Commission's new approach to implementing its role under the Euratom Treaty.

4. References

[1] J. L. Jaech, "Statistical Methods in Nuclear Materials Control", Technical Information Center, Office of Information Services, US Atomic Energy Commission, 1973.

This is a detailed treatment of how MUF standard deviations can be computed for a large variety of situations. For somebody working in a facility, this is the topic of most importance. The treatment is accessible for readers having only a basic knowledge of statistical theory.

[2] "Statistical Concepts and Techniques for IAEA Safeguards", 5th Edition, Department of Safeguards, IAEA, 1998.

This is a manual of all the statistical methods employed by the IAEA. It includes the methods for designing adequate verification plans for inspectors and data evaluation for drawing conclusions from verification results. The treatment is accessible for readers having only a basic knowledge of statistical theory.

[3] M. T. Franklin, "Sampling Theory in the Auditing of Nuclear Materials Accountancy" EUR 21681 EN, published by the Institute for the Protection and the Security of the Citizen, Joint Research Centre of the European Commission, 2005.

This presents a formal description of much of the statistical theory underlying the use of statistical methods in the verification of nuclear material control. The treatment is accessible for readers having a specialist level of knowledge of probability theory and statistics.

Electronic Safeguards Seals

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1. Introduction

The compliance verification related to the Treaty on the Non-proliferation of Nuclear Weapons of 1968 is based, among others, on the application of technical measures in nuclear facilities. Verified nuclear materials are monitored using containment and surveillance (C/S) techniques which help to ensure the timely detection of a diversion by the early detection of, e.g., the opening of a container or access to a storage area. Thus, C/S measures aim at ensuring both the completeness and the continuity of knowledge of verified material flows and inventories.

C/S measures are designed to indicate anomalies as compared to verify the presence of nuclear materials, and their role is considered complementary to nuclear materials accountancy and measurements. However, present generation nuclear facilities such as large-scale commercial reprocessing and mixed-oxide fuel fabrication plants, long term spent fuel storage and spent fuel conditioning facilities require highly automated and customized safeguards systems an essential part of which is based on C/S techniques.

C/S techniques have evolved from commercially available cap-and-wire seals and amateur film cameras to modern integrated monitoring systems with the capability to combine different types of C/S devices such as digital image surveillance and electronic sealing. The use of modern safeguards specific C/S techniques has a great potential to enhance the efficiency and effectiveness of safeguards and cope with new challenges arising from the International Atomic Energy Agency's (IAEA) Integrated Safeguards in connection with the implementation of the Additional Protocol [INFCIRC/540 corrected, December 1998]. Seals are applied, in order to avoid re-measurement of verified items or samples and, thus, save inspection effort.

The major user requirements related to electronic seals are unattended operation, tamper resistance, data authentication, in situ data retrieval, remote retrieval of encrypted data, re-usability, capability for interfacing with digital image surveillance, capability for operation by both the safeguards authorities (IAEA, national, regional) and facility operators, and independence of the facility operator's power supply.

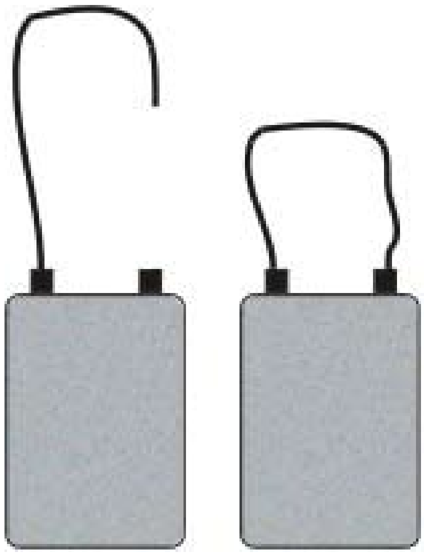
The IAEA currently uses about 1,500 VACOSS electronic seals in attended and remote monitoring applications [1]. These seals may be applied to spent fuel transport and storage casks, concrete lids of power reactors, doors and gates of storage areas, piping, and containers with special nuclear material. Furthermore, there have been applications, where the plant operator was authorised to attach or detach a VACOSS seal under camera surveillance with the seal data being stored not only in the seal but also in the associated video image. To this end, a special seal-video interface is available.

The IAEA has started a replacement programme of the VACOSS seal, which has been in use for about 15 years.

2. Description of the Technique

2.1. Sealing Principle

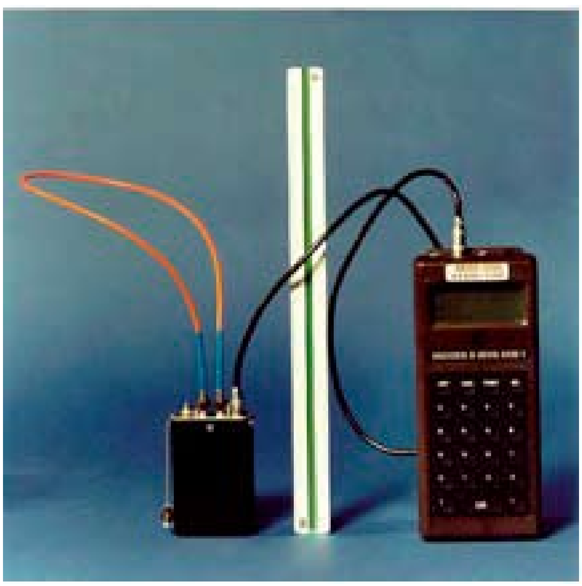
The sealing principle can be described as a padlock. The sealing function is realised by using a fibre-optic cable (FOC) or, alternatively, an electrical wire. The FOC or wire is looped through the locking mechanism of the container or site to be sealed and the two ends attached to the seal body. The fibre-optic concept has a light source (i.e., optical transmitter) and a light sensor (i.e., optical receiver) with the light being transmitted through an external FOC of practically arbitrary length. In the wire concept the electrical current is monitored as well as the resistance of the wire. Both concepts are designed for multiple connection and disconnection of the FOC or wire, i.e., "closing and opening of the seal". The FOC or wire can be manually "opened", i.e., disconnected, and "closed", i.e., connected, without using any tool. Every opening and closing is monitored and registered by the internal micro-controller with annotation of date and time.



Sealing principle: fibre optic cable/wire “open” or “closed”

2.2. Description of the Implemented Technique

The VAriable COding Sealing System (VACOSS) [2,3] consists of a seal body containing the electronic circuitry and battery, a fibre optic cable, and an interface box to provide communication between the seal and the reader. Initially, the seal reader was a dedicated handheld device with firmware. Currently, it is basically a dedicated software running on a palmtop or laptop PC. The seal is re-usable, and the data stored in the seal can be retrieved in situ. It is mainly used for applications were multiple openings and closings are expected, or when the seal is combined with a remote monitoring system. The seal operates on battery, and the battery life in the field is 18 months.



VACOSS-S seal and reader (1991)

EOSS seal (2004)

2.3 New Electronic Seals

The Integrable Re-usable Electronic Seal (IRES) [4] has been developed under the French Programme in Support of the IAEA. It can be used with both a FOC and an electrical wire, while the seal detects whether it is being used with a FOC or a wire. The FOC is a multimode cable and the light source is a light emitting diode (LED) emitting random frames (8 bits) every 500 μs in the infrared range. Communication with the seal takes place via a serial RS485 interface or wireless link (radio module). The IRES seal is available for use and could be adapted, if necessary, according to the demands.

The Electronic Optical Sealing System (EOSS) [5] has been developed under the German Programme in Support of the IAEA. It is used with a FOC only. The FOC is a single mode fibre, and the light source is a laser. The open/closed status of the FOC is monitored by transmitting and receiving short light pulses at certain time intervals. Communication with the seal takes place via a serial RS485 interface. In November 2005, the IAEA approved the EOSS seal “for routine use” (category A). In 2006, the IAEA began to procure it for replacement of the VACOSS seal.

The VACOSS 5E has been developed under the US Programme in Support of the IAEA. It is used with a FOC only. The FOC is a multimode fibre, and the light source is a LED. The open/closed status of the FOC is monitored by transmitting and receiving light pulses at certain time intervals. Communication with the seal takes place via a serial RS485 interface. The development of the VACOSS 5E seal was terminated. Currently, there are no plans to implement the VACOSS 5E seal.

IRES seal (2004)

VACOSS seal (2002)

3. Other Fields of Application

It is conceivable that the electronic seals developed for international safeguards have a potential to be applied also in the area of arms control.

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Monte Carlo Simulation applied to non-destructive assay techniques

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1. Objective of the technique

Monte Carlo simulations are commonly applied to non-destructive assay (NDA) systems both as a design tool for NDA equipment, to optimise its performance and to predict its response in different configurations, and as a computational calibration technique. Computation codes based on the Monte Carlo method allow the modelling of complex geometries in three dimensions and determination of the response of an NDA instrument without the need for nuclear standards.

2. Presentation of the technique

2.1. Principle of Monte Carlo simulations

The Monte Carlo method does not solve an explicit equation, but instead obtains answers by simulating individual particles and recording aspects of their behaviour. Numerous particles are followed from their emission by a source, through to their loss by absorption or leakage. The trajectory of each particle is broken down into sequences comprising free flight and, at a given moment, a collision whose nature is randomly selected from a set of possible reactions in the material, the assigned probabilities being related to the cross sections of the material in question.

The behaviour of real particles within the physical system is predicted from the accumulated data on a large number of simulated particles, and the response of the NDA instrument is determined from the statistical mean of the behaviour of the population of the simulated particles. This technique is well suited to solve complicated three dimensional and time dependant problems, because no averaging approximations are required in space, energy or time.

Thus an NDA system can be modeled and the expected response from the detection system can be calculated. The simulation can be applied to a range of detectors (high purity germanium detector in the case of gamma spectrometry, ^{3}He detectors in the case of neutron counting devices), used with a variety of radioactive sources including containers holding nuclear materials and drums containing neutron- and gamma-emitting waste.

2.2. Monte Carlo simulation technique

Implementation of a Monte Carlo computational code requires the preparation of an input file that describes the geometry of the system in three dimensions, the materials, the associated cross-sections libraries (built using standard nuclear data evaluations), the location and characteristics of the emitting source, the type of results desired and the conditions for running the calculation.

The code MCNP [1], considered as an international standard code for neutron, photon and electron transport modelling, is commonly used in support of the design and calibration of NDA systems for nuclear material safeguards applications. The user can instruct the code to make various tallies related to particle currents, particle flux, reaction rates in different points, surfaces or volumes of the system and energy depositions. Each tally is given by the code with a statistical relative error, representing the precision of the Monte Carlo calculation. Depending on the number of particles generated, the error can be as small as desired by the user, given sufficient time to complete the calculation. In addition to the tally information, the output file also contains tables of standard summary information that can help the user to determine the confidence in the results.

- **Example 1: modelling of an experimental gamma-ray spectrometry system :**

The experimental gamma ray spectrometry system presented in **Figure 1** is used to quantify plutonium masses present in waste drums. The MCNP computation code enables estimation of the energy spectrum of the photons detected in the detector's germanium crystal (**Figure 2**) for any gamma source facing it. The energy deposition from those electrons generated by the photons impinging upon the detector is calculated, for each emitted photon, from:

- a 3D description of the detection system formed by the detector, its stand and collimator, in its measuring environment (**Figure 3**). This model incorporates the physical (density), chemical (stoichiometry) and nuclear (cross sections) data characteristic of each material; and

- a geometrical description of the photon source, its location in relation to the detector and the definition of its emission.

Figure 1 : gamma spectrometry system

Depending upon how complex the photon source is (i.e. calibration source or nuclear material), one or two calculation stages may be required in order to estimate the spectrum. In the case of nuclear material, the effect of self-absorption can lead to a requirement for a two-stage calculation process, for reasons of statistics and computing time. This two-stage process comprises calculating the photon flow from the radioactive object at the input side of

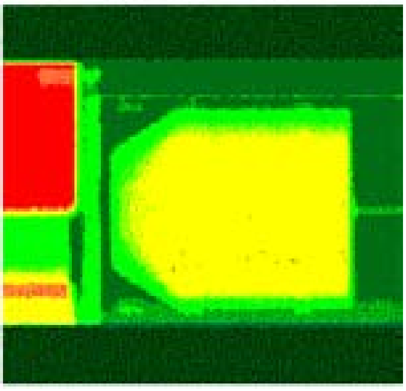

Figure 2 : radiography of the crystal

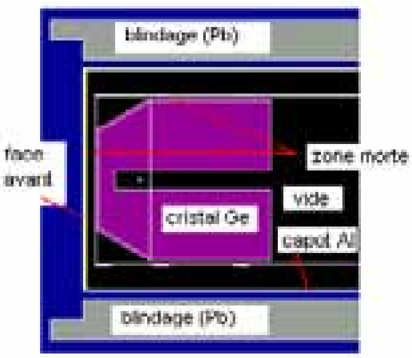

Figure 3 : axial section

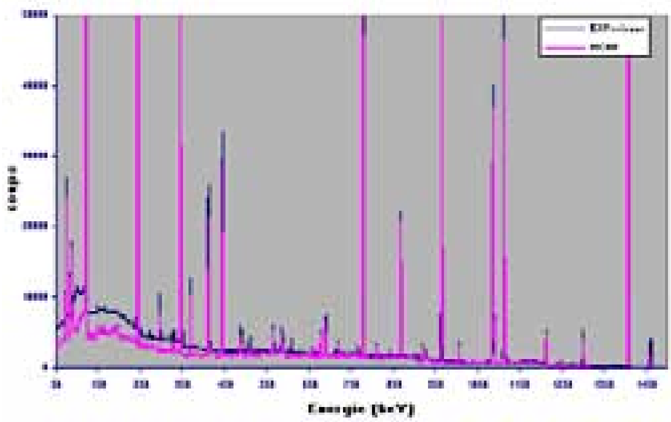

Figure 4 : ^{152}Eu spectrum

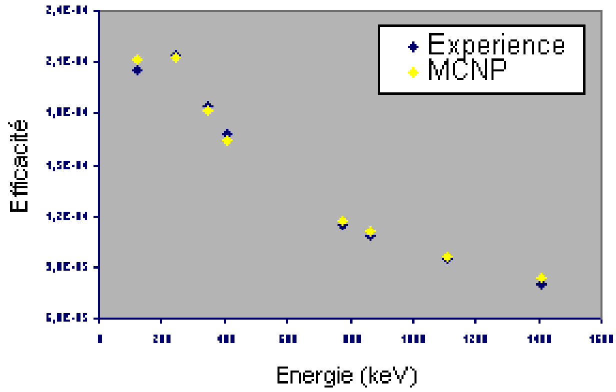

Figure 5 : efficiency curve

the detector, then calculating the detector's response to this flow at normal incidence.

The modelling validation phase entails establishing a calibration curve for the efficiency of the gamma-ray spectrometry system. The calibration is carried out experimentally using a certified ^{152}Eu source, particularly useful because its γ emission spectrum is spread over an energy interval ranging from 121 - 1408 keV (spectrum **Figure 4**). The model can be improved, by giving a very accurate description of the detector's shape and by adjusting the peripheral dead zone thickness in the manufacturer's recommended range, to obtain constant deviation for all the ^{152}Eu lines. The calibration curve produced is presented in **Figure 5**, showing relative deviations between the experimental efficiencies and those set by MCNP of between - 2% and +4% for the main ^{152}Eu lines.

Such a model can be applied to the calculation of spectra relating to real plutonium waste drums, for measurement feasibility studies. In this case, allowance can be made for the container, the matrix comprising the drum (physical and chemical composition, density, homogeneity), the radioactive material (activity level, position) and the presence of other, more intense, gamma-ray emitters (fission

Figure 6 : neutron counting system

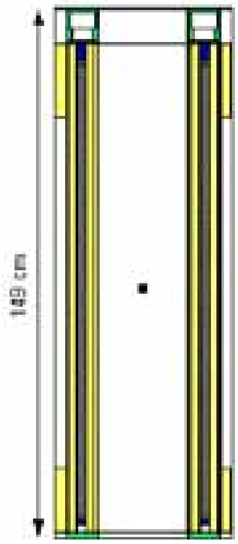

Figure 7 : axial section

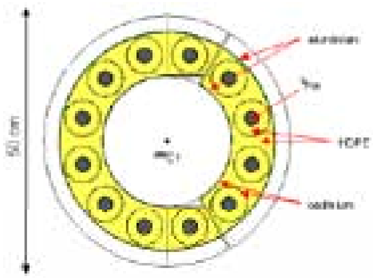

Figure 8 : radial section

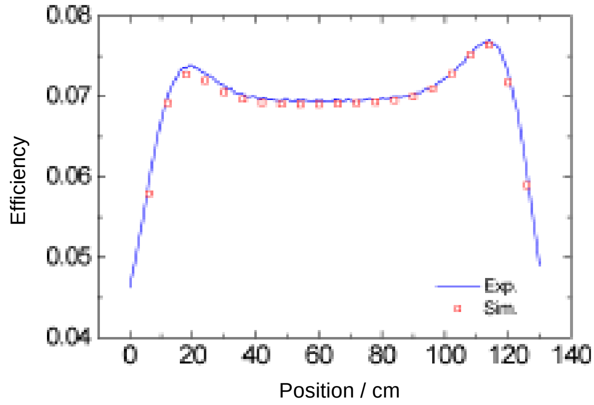

Figure 9 : axial profile of totals

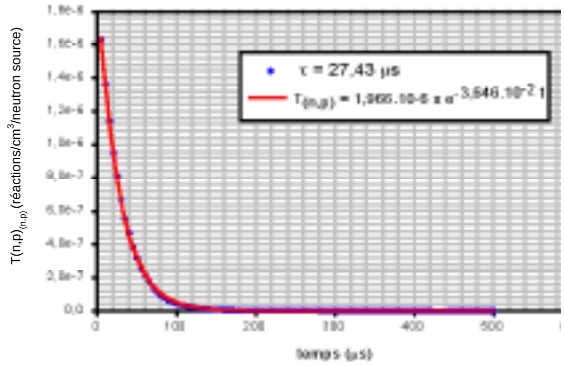

Figure 10 : neutron lifetime

and activation products) when evaluating the detection limits of the NDA system.

In gamma spectrometry, Monte Carlo simulations can also be used to determine the function of energy transfer, and to evaluate the influence of the geometry of the system (i.e. source to detector distance, photon attenuation in packages or screens, collimation system), for each energy.

- Example 2 : modelling of an experimental neutron counting system :

The passive neutron counting system shown in **Figure 6** is used to measure plutonium held in large-dimension containers. The MCNP computation code enables an estimation of the neutrons detected by the neutron counting system for any neutron source placed inside the measuring cavity. The code calculates the number of neutron captures (n, p) occurring in the active parts of the twelve detectors, for a neutron emitted by the neutron source. The code employs:

- a 3D description of the measuring chamber (**Figures 7 and 8**), including the physical (density) and chemical (stoichiometry) and nuclear (cross sections) characteristics of the materials; and
- a geometric description of the neutron source, its location in the sample cavity and the definition of its emission.

The modelling process goes through an initial phase, to assess the quality of the model through examination of some characteristic parameters of the NDA system. This entails comparing practical measurements of the detection efficiency and neutron lifetime, using a calibration source of ^{252}Cf, against the simulated parameters. **Figure 9** shows the efficiency axial profile, obtained experimentally and by MCNP simulation, illustrating a 2% deviation in the simulated results from the experimental values. **Figure 10** presents the evolution of the number of (n,p) captures in the detectors over time, obtained by simulation with MCNP, for a source of ^{252}Cf centered in the sample cavity. The number of neutrons present in the device drops exponentially over time, with a mean lifetime of λ, with a 3% deviation in the simulated results compared with the experimental values.

A model is built as realistically as possible, but it is very hard to describe accurately all the components of the measurement system. Because it is important to have a thorough knowledge of the materials that form the neutron moderator and absorber, hypotheses and verifications are made in order to arrive at a better description. In the case of the detector tubes, the manufacturers give some parameters, such as the active length or fill pressure, but wall thickness and material, end caps and added gases are harder to establish. As the quality of the simulation is a function of the approximations made, parametric studies are used to quantify the influence of data known to be inaccurate and its uncertainty on the result. A compromise has to be found between the detail of the description and the required accuracy.

Such a model can be applied to calculation of the neutron count rates relating to large plutonium samples, and new Monte Carlo codes based on MCNP, such as MCNP-PTA or MCNPX, are being developed for this purpose. Neutron pulse trains are generated in the Monte Carlo simulation, and analysed in a simulated shift register in order to predict the expected singles, doubles and triples that would need to be measured experimentally in order to quantify plutonium [2]. The simulations performed with such modified MCNP codes give the opportunity to carry out a calibration when a fully representative standard for experimental calibration is not available.

3. Performance

Upon completion of a Monte Carlo simulation, the computational code used gives a statistical uncertainty dependent upon the number of particles that contributed to the result, so that the correct convergence of the calculation can be checked. The selection of a statistical error criterion often results from a compromise between calculation time and the required accuracy of the result. But this is not the only contribution to the overall uncertainty of the simulated quantity, and this error does not represent the accuracy of the result compared to the true physical value.

Monte Carlo simulation is limited by the validity of the assumptions and the accuracy of the model used. These limitations come from the level of detail of the geometry model, the accuracy of each input data used during the calculation (material data, nuclear data), the physics treatments and any other interpretational models used to convert calculated quantities into a representation of the instrument response. The uncertainties arising from the differences between modelling and reality (description simplifications, lack of knowledge of some data etc) are estimated using both sensitivity studies, by assessing which relative influence of variation in each parameter on the result, and benchmarking against experience.

- **Example 1 (modelling of an experimental gamma-ray spectrometry system).:**

To obtain good agreement between calculation and experience, very accurate information is required on: the detector (geometry, dead zones); the shielding (composition, density); the sources (mass, density, composition, geometry); the containers; and the matrix, if any. The study performed showed an uncertainty on the detector efficiency above 100 keVof about 5% if the geometry of the crystal was accurately known. The modelling of plutonium oxide samples with a relatively well known geometry presented an uncertainty of about 20% on the net area of total absorption peaks from 129 keV to 451 keV.

- **Example 2:**

A parametric sensitivity study of the nuclear (spectra, cross sections), geometric (^{3}He detectors position, tubes thickness), physical (density), chemical (composition) and environmental data (repository premises) lead to an overall uncertainty on the detection efficiency of the system of about 5%. Modelling of plutonium oxide samples with a well-known geometry and a plutonium mass from 8 to 2500 g gave an accuracy of about 2 % on the total neutron rates.

The ESARDA NDA WG organised a simple benchmark exercise [3] involving a neutron slab monitor, to study the influence of the nuclear data, physics treatments and geometry model approximations employed by commonly used Monte Carlo codes and to demonstrate the typical level of agreement with measurement that might be achieved for a simple neutron case. The results showed that Monte Carlo modelling could achieve agreement to within 5% of that from experiment, for simple geometries, with an uncertainty of about 3% due to geometry and physics treatments.

A previous benchmark exercise focused on the prediction of reals for a uranium oxide fuel assembly mounted inside the cavity of a neutron coincidence collar [4]. This indicated a performance value of 10% for the reals prediction techniques, based on an analogue Monte Carlo technique or on a modified form of the point model.

The ESARDA NDA WG is now working on a document describing recognised industry best practice techniques for the application of computer modelling tools in NDA.

4. Additional information and useful links

[1] «MCNP – A General Monte Carlo N-Particle transport Code. Version 4B».
J. F. Briesmeister
LA – 12625 – M, Version 4B. Manual.

[2] «Passive Neutron Coïncidence Counting Techniques for Pu mass determination».
ESARDA technical sheet.

[3] «Results of the Monte Carlo « simple case » benchmark exercise».
Patrick Chard
ESARDA symposium, 2003.

[4] «Results of the ESARDA REALS prediction benchmark exercise».
P. Beaten et al.
ESARDA Bulletin N°31.

http://laws.lanl.gov/x5/MCNP/index.html

NB: a "Good Practice Guide for the use of computer simulations techniques in non destructive assay" is under construction by the ESARDA NDA WG.

Gamma Spectrometry for U and Pu Isotopic Determination

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1. Objective of the technique

Gamma spectroscopy is the most commonly used Non-destructive Assay (NDA) technique in nuclear safeguards to measure uranium enrichment and plutonium isotopic composition [1].

2. Presentation of the technique

2.1. Principle of measurement / Definition of the physical principle

The decay of radioactive nuclides is often accompanied by the emission of one or more photons whose energy is characteristic of the nuclide itself. Gamma spectrometers are equipped with detectors appropriate for measuring the photon energy. Therefore, a gamma spectrum can be used to identify the gamma emitting isotopes in a material by correlating the photopeaks to the characteristic energies of each nuclide. Moreover, the comparison of different peak intensities can be used to derive the relative abundance of isotopes.

There are several types of gamma spectrometer, with different applications [2]. The most common types used in safeguards applications are:

- inorganic scintillators, mostly NaI(Tl) detectors
- semiconductor detectors, such as high-purity germanium (HPGe) or cadmium-zinc-telluride (CZT).

In a scintillator, the interaction of the photon with the crystal results in the excitation of atoms to higher-energy states, followed by their immediate relaxation with consequent emission of the excitation energy in the form of light. This light is collected on a photocathode, composed of a material with a high probability of photoelectric effect, resulting in the emission of a number of electrons proportional to the energy of the original photon. These electrons are then increased in number by successive acceleration in an electric field and collisions on metallic dynodes, finally resulting in a charge burst hitting the anode of the photomultiplier tube.

In a semiconductor, the photon "ionises" the crystal (i.e., by generating electron-hole pairs), and this results in a collection of charge at the electrodes, if a voltage is applied to the semiconductor.

In both cases, the interaction of a photon with the detector results in an electric signal, whose intensity is proportional to the energy of the incoming photon.

The analogue signal is then processed in a pulse processing electronic chain. This typically consists of an amplifier, an analog-to-digital converter (ADC) and a multi-channel-analyser (MCA) that produces the gamma spectrum. The gamma spectrum is simply the number of photons detected in a preset number of channels, each channel corresponding to an energy band. The analogue modules may also be integrated into a single compact module, such as the MMCA (Mini Multi-Channel Analyser). Recently, the traditional analogue electronics have been replaced by digital electronics, and DSP (digital signal processor) modules are now available.

Finally, the spectrum is analysed in a PC using specialised software, performing peak fitting, background subtraction, peak intensity calculation, external or intrinsic calibration and calculation of the relative isotopic abundance.

2.2 Measurement technique / Description of the implemented technique

a) Acquisition of gamma spectra

Scintillators in general, and NaI in particular, are characterised by a high detection efficiency, counterbalanced by a poor energy resolution[1]. Due to this last feature they are not suitable for cases involving complex spectra with many closely spaced gamma lines, such as plutonium. The use of NaI detectors in nuclear safeguards, often referred to as Low Resolution Gamma Spectrometry (LRGS), is therefore limited to the measurement of ^{235}U enrichment in uranium samples.

1 Due to the statistical nature of the physical processes involved in the conversion from photon energy to electric pulse, a photon with a well-determined energy generates an electric pulse whose intensity can fluctuate around an average value. This results in a broadened peak shape in the spectrum instead of a line. The resolution of a detector is defined as the ratio between of the full-width-at-half-maximum (FWHM) of the peak and the photon energy.

High Resolution Gamma Spectrometry (HRGS) is the preferred technique for plutonium isotopic determination, although it can also be applied to measure uranium enrichment. HPGe detectors have by far the best energy resolution. Unfortunately, germanium crystals cannot be operated at room temperature. To guarantee an appropriate semiconductor behaviour, the germanium crystal has to be maintained at very low temperatures, i.e., typically using liquid nitrogen (77 K) or electro-mechanical systems. Due to the required cooling, germanium detector units tend to be relatively heavy and large (see photos at the end of this paper).

For applications where portability or accessibility is an important requirement, other types of crystal have been introduced, such as Cadmium-Zinc-Telluride (CZT), which exhibits semiconductor behaviour at room temperature. CZT detectors have a lower energy resolution than Ge-detectors and are used to measure uranium enrichment and to perform attribute verification of spent fuel (detection of fission products). Figure 1 shows a comparison of typical spectra as generated from different types of photon detector.

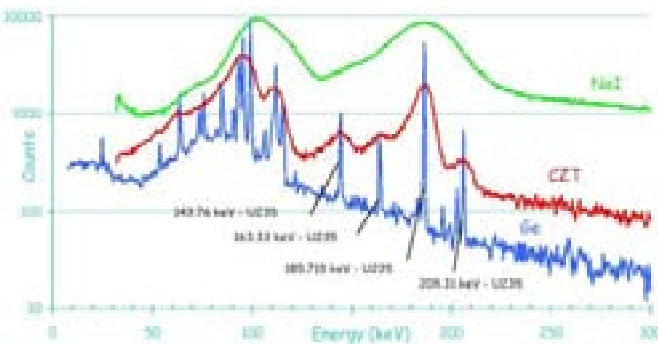

Figure 1 – Comparison of uranium spectra from different detector types [3]

b) Analysis of gamma spectra

Once a spectrum has been acquired it has to be evaluated, in order to derive the isotopic composition. There are basically two methods available for the analysis of spectra:

- infinite thickness method (or enrichment meter principle)
- intrinsic calibration method.

Gamma spectrometer with liquid nitrogen-cooled germanium detector, Mini Multi-channel Analyser, and Hewlett Packard LX200 palmtop computer

The infinite thickness method is applied only for uranium enrichment measurements, and it is based on a calibration using reference samples. According to this approach, the most prominent gamma transition of 185.7 keV from the decay of ^{235}U is measured under a well-defined geometry (i.e., solid angle of the sensitive detector volume relative to the gamma source). The measured counting rate of the 185.7 keV photons is proportional to the ^{235}U abundance. The required infinite sample thickness ranges from about 0.25 cm for metal samples to about 7 cm for UF_6 with a density of 1 g/cm^3. The method is best suited for bulk samples (e.g., uranium oxides and fluorides in storage containers), which easily meet the infinite thickness requirement. Enrichment measurements based on the enrichment meter principle require physical standards containing

Table 1 — Performance values for gamma-spectrometric enrichment measurements on low-enriched uranium oxide materials

^{235}U Enr.	Infinite thickness method									Intrinsic calibration method					
	HRGS (Ge detectors)			LRGS (NaI detectors)			CZT			HRGS (Ge detectors)			CZT		
	CT (s)	r (%)	s (%)	CT (s)	r (%)	s (%)	CT (s)	r (%)	s (%)	CT (s)	r (%)	s (%)	CT (s)	r (%)	s (%)
0.3 to 0.7%	360	2	1	360	3	1	1200	10	1	360 3600	8 3	5 5	ns	ns	ns
2 to 4 %	360	0.7	0.5	360	1	0.5	1200	3	1	360 3600	2 1	1 1	104	10	5
5 to 10 %	360	0.5	0.5	360	0.5	0.5	1200	3	1	360 3600	2 1	1 1	104	10	5

Table 2 — Performance values for Pu isotope assay in PuO2 and MOX

Type of plutonium	Isotope	r (%)	s (%)
Low burnup	^{238}Pu	3	5
	^{239}Pu	0.2	0.1-0.2
	^{240}Pu	1	0.3-1
	^{241}Pu	1	0.2-0.6
	^{241}Am	1	0.5
High burnup	^{238}Pu	1	1
	^{239}Pu	0.5	0.2-0.4
	^{240}Pu	1	0.5-1
	^{241}Pu	1	0.5-1
	^{241}Am	1	1

a sufficiently large amount of uranium reference material for calibration.

Measurements based on the intrinsic calibration method avoid the need for calibration with physical standards. Here, the isotopic ratios are determined from the measured gamma spectrum using corresponding gamma and X-rays from the decay of all isotopes, taking into account physical phenomena such as the energy dependence of detector efficiency, self-absorption in the sample and attenuation in the container and filters. For plutonium spectrum analysis, a major advancement for the measurement technique was achieved with the development of the Multi-Group Analysis (MGA) code, which successfully exploits the complex XK_α region (94-104 keV) of a plutonium gamma spectrum for the isotope analysis [4]. Since this spectral region contains the most abundant plutonium gamma and X-rays detectable in a gamma spectrum from plutonium in the presence of Am, use of MGA code enables relatively precise isotope abundance determinations from gamma spectra accumulated in relatively short counting times (15-30 min). For uranium spectra, the method again uses analysis of the XK_α region (89-99 keV), where fairly abundant but strongly overlapping gamma and X-ray signatures from the ^{235}U and ^{238}U daughter nuclides ^{231}Th and ^{234}Th occur. This approach requires secular equilibrium between ^{238}U and its daughter nuclides, which is reached about 80 days after chemical separation: the method is, therefore, not suited to freshly separated uranium materials.

Germanium detectors with dewars for liquid nitrogen cooling

A drawback of the gamma-spectrometric technique is the lack of measurement capability for the isotope ^{242}Pu. Because of its very low specific gamma activity, ^{242}Pu does not manifest itself with a detectable gamma-ray signature in a plutonium gamma spectrum. Therefore, recourse has to be made to isotope correlation techniques for an estimate of the abundance of this isotope. The uncertainty in the estimated ^{242}Pu abundance reduces the overall accuracy of a complete gamma-spectrometric plutonium isotopic analysis made on materials containing a notable fraction of this isotope.

2.3. Performance Values for gamma spectrometry

For uranium enrichment measurement there is a variety of methodological possibilities according to the choice of the detector (NaI, HPGe or CZT) and of the analysis method (enrichment meter or intrinsic calibration). Table 1 compares typical performance values of the possible combinations [4] as a function of the enrichment range. In this table CT stands for counting time in seconds, and “r” and “s” stand for the contributions to the measurement uncertainty derived from the statistical (random) and systematic components respectively.

For plutonium isotopic composition the choice of HPGe in combination with intrinsic calibration is the only option available. Table 2 shows typical performance values for HRGS technique for different plutonium compositions. The random component of the uncertainty is based on the assumption of a typical counting time of 10 to 20 minutes. The systematic uncertainty is estimated based on the use of a well-known isotopic ratio of ^{242}Pu. If this value is not known, and has to be computed from isotopic correlations, the systematic uncertainty can increase significantly, being dominated by the uncertainty of the ^{242}Pu content.

3. Additional information and useful links; references

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[3] R. Berndt, P. Mortreau, "Handbook of Gamma Spectrometry Methods for Non-destructive Assay of Nuclear Materials", EUR 19822 EN, revision 2, June 2004.

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[5] S. Guardini (editor), "Performance Values for Non-Destructive Assay (NDA) Techniques applied to Safeguards", ESARDA Bulletin No. 32, March 2004.

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