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Editorial

A few points for the Editorial

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The ESARDA symposium took place in Aix-en-Provence (France) from 22 to 24 May 2007 and was attended by more than 260 participants. More than 160 papers were presented in 30 sessions including a poster session of about 30 posters.

This was the biggest event ever organised by ESARDA both by number of attendees and number of presented contributions. The practical organisation was a real success thanks to the outstanding involvement of IRSN, member of ESARDA. In general the symposium was very well received by participants.

Proceedings are planned to be issued end of August 2007 by the Secretariat.

The Symposium gave the opportunity to hear about new topics and also allowed a chance to improve and reinforce existing contacts and collaborations as well as creating new ones.

From the Symposium two subjects have emerged: "export control of dual use items" and "Communication, education and training", which both have had a dedicated session for the first time. Others are still in shape such as the "Integrated Safeguards", NDA, "C/S and remote monitoring" of which there were 4 dedicated sessions each.

Other topics of importance were reported such as SNRI (short notice random inspections). Other areas touched upon were security, nuclear forensics and illicit trafficking.

The NMACAF report was presented during the symposium itself and at the Steering Committee and unanimously welcomed.

During this symposium ESARDA has touched upon several areas which are nowadays influencing nuclear safeguards. ESARDA will continue to focus on research and development in the safeguards area but there is obviously a need for ESARDA to obtain enough knowledge on the other topics because it is the combination of all these that in the near future, if not already today, will be the main elements of nuclear non-proliferation.

10 years ago at the Montpellier Symposium, the IAEA was announcing that the Board of Governors had approved the Additional Protocol to the Safeguards Agreements. ESARDA reacted by creating a Working Group on Integrated Safeguards.

During the past 5 years, 3 wise men have reported to the Commission about safeguards to be implemented by Euratom. As a reaction to the proposal in the report on a more audit focused control ESARDA created the Nuclear Material ACcountancy and Audit Focus (NMACAF) Group which has released its report at this symposium.

Two years ago the Training and Knowledge Management Working Group (TKM) created a course for young students or practitioners in safeguards. This year the course was held in Ispra, in which 62 trainees participated.

The Verification Technologies and Methodologies Working Group (VTM) deals with various aspects of treaty verifications and has launched an activity on export control of dual use items.

As mentioned, above forensics, Illicit trafficking, Security, are topics of interest and ESARDA, an association dealing with technical matters will consider if it should enlarge its scope of activities.

So many subjects are to be explored where ESARDA members can bring experience in the field.

The Editorial Committee will take care of the feedback of the symposium in order to prepare the ground for facilitating the organisation of further events and maximise the probability of success. The follow up will consist in re-examining the communication policy of ESARDA and the role of symposia, internal meetings in Luxembourg and bulletin.

The Bulletin is published twice a year.

Most of the Working Groups had their regular meetings in the vicinity of the symposium. To be noted: several side meetings took place (the safeguards expert group of the Atomic Questions Group of the Council – ESARDA was thanked by the German presidency of this group, Mr. Remagen, the international safeguards division of INMM, Euratom US DoE review meeting, IAEA and French Support programme, etc.). This confirms that the ESARDA symposium is an attractive event, built on by participants for their various safeguards concerns and projects and that the ESARDA symposium opens an important opportunity for different groups of interest to meet and further develop their co-operation in the safeguards area.

During the Steering Committee meeting, 5 new members were welcomed to join ESARDA: the Regulatory Authorities of Romania, the Norwegian Radiation Protection Authority, the Swiss Federal Office for Energy, Sellafield Plc. and one individual member (B. Burrows). ESARDA counts now 25 members. Other organisations involved in the fuel cycle are considering joining ESARDA.

The Audit Group report was presented and very well received. The outcome of the report will be followed up in the Integrated Safeguards WG. The next annual meeting is planned to take place in Luxembourg from 25 to 30 May 2008. There are parties who have shown interest in organising the next symposium (2009) and ESARDA hopes that a decision can be taken at the next Executive Board meeting to be held in October.

With this I would like once again to thank the IRSN for its excellent organisation of this 2007 ESARDA Symposium. I would also like to take the opportunity to thank all the chairs who managed to keep the sessions go so smoothly and finally I welcome all the participants to the next ESARDA symposium at another interesting place in Europe.

Fifty Years of Safeguards under the Euratom Treaty – A Regulatory Review

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Please note, the following paper was previously presented at the 2007 ESARDA Symposium and therefore will also be published in the proceedings.

Abstract

March 2007 marked the 50th anniversary of the signing of one of the founding treaties of the European Community. The Euratom Treaty has its origins at a time when the stability of energy supplies in Europe was a major concern. Recently, much debate has centred on the possible reform or repeal of some parts of the treaty, given that its original aim was to promote and oversee the development of nuclear energy in Europe. This debate has focused attention on the future contribution of nuclear power to increasing energy demands in an enlarged Europe. However, despite these issues there is near universal agreement that the Euratom Treaty has played a vital role in the protection of European citizens through the controls required for nuclear materials.

Chapter VII of the treaty (Safeguards) confers wide regulatory powers to the European Commission to ensure that civil nuclear materials are not diverted from their intended use as declared by the operators. This paper describes the early period of operation of the safeguards inspectorate, and gives statistics on the numbers and types of inspections carried out by the Euratom inspectors, and discusses from an operational point of view the value of inspection activities. Further, a critical appraisal of Articles 77-85 within Chapter VII is made. The paper also considers those safeguards requirements that are important to strengthen, in order to maintain a strong regulatory system to oversee future challenges, particularly in the context of increasing decommissioning activities within Europe.

It is noteworthy that fifty-years after the founding of the treaty, many of the concerns about security of energy supply have re-emerged. It is a measure of the vision and forward thinking of its founders that the treaty has successfully overseen the safe and secure development of nuclear power in Europe (which currently provides a third of its electricity needs) and despite the many changes and developments that have occurred, that the objectives concerning safeguarding nuclear materials have been met as intended. The controls envisaged at that time remain fully relevant today.

Keywords: Euratom treaty; safeguards

1. Introduction

In the 1950s, nuclear power was heralded as a solution to future energy needs, and was poised for rapid expansion. Whilst technically capable of exploiting nuclear energy, Europe at that time lacked sufficient enriched uranium resources. The priority was for European community countries to rapidly develop the necessary technology and acquire nuclear material to successfully use nuclear power for their energy needs. As well as developing links with other countries for the supply of the material, there were research goals, sharing of information, and making best use of resources. To provide a cooperative means of sharing technology, to jointly develop the newly emerging nuclear power resource for civilian benefit, and to further European integration after the previous war, the European Atomic Energy Community (EURATOM) was established with the signing of the Euratom treaty in 1957 by the 6 founding member countries (France, Germany, Belgium, Italy, Netherlands, and Luxembourg).

The tasks entrusted to Euratom were many – to conduct research, to establish uniform safety standards for health protection of workers and the public, to guarantee the equitable supply of ores and nuclear fuels to users, to exercise the right of ownership of special fissile material, to facilitate commerce in the nuclear market, to establish relations with third countries and international organisations promoting civilian uses of nuclear power, and to ensure by appropriate supervision that nuclear materials were not misappropriated

from declared uses [1]. From the outset it was recognised that to mitigate the risks of militarisation of the nuclear materials associated with the civil nuclear industry, a safeguards system capable of accounting for the movement and stocks of nuclear material was essential. Thus the dual role of the (Euratom) Commission was created – firstly to promote, but also to apply controls and regulate the holding and transfer of nuclear materials.

Today, there are many who argue that the Euratom treaty is obsolete, and that the original aims to promote nuclear power are out of step with current priorities. Some point to the democratic deficit in the treaty, the lack of accountability to the European parliament [2, 3]. Others criticise the dual regulator/promoter role of the European Commission. Much has also been written about the overlap of responsibilities with the NPT requirements of the IAEA and the functions of the two organisations.

In the 50 years since its inception, it is therefore pertinent to ask what has been the contribution of the Euratom treaty to the safe development of nuclear power in Europe. How well have the treaty objectives (Chapter VII) to control and safeguard the nuclear material been met? This paper concentrates on this latter aspect of the Euratom treaty objective, starting with very brief descriptions of the background to the treaty and then the key features of safeguards development, and statistics showing the growth in safeguarding activities, followed by an appraisal of the treaty outcomes.

2. Background to the founding of the Euratom Treaty

One of the primary ideas for a European Atomic Energy Community was to serve as a catalyst for the wider goal toward European integration through European Economic Community. The founders of the Community saw the potential of joint cooperation in the emerging nuclear power resource as an example of the benefits of community integration [3]. The period of the 1950's was also characterised by concerns about the limited sources of fuel oil, and the expanding energy demands of the post-war European countries. This was put into sharp focus by the 1956 Suez crisis that revealed EuropÈs fragile access to Middle Eastern oil reserves. At the time, individual countries in Europe had already begun to establish national nuclear research and development programmes, although much of the nuclear technology and nuclear material (enriched uranium) was in the hands of the USA, Canada and Great Britain. The "Atoms for Peace" initiative of the US in 1953 allowed the transfer of technology and

materials to participating countries for civil nuclear power use under condition of strict safeguards to prevent diversion to military use. The original signatories to the treaty sought to accelerate progress by creating centres of knowledge and expertise as well as acquisition of the nuclear material for civilian uses.

However, the negotiations for the treaty were far from smooth. National interests continued to take precedence over community interests – for example in the desire to develop a national nuclear weapons capability whilst restricting the access of other countries to the materials necessary [4]. Divergent national interests, different economic and administrative approaches and the question of whether member states had the right to develop a nuclear deterrent meant that the final treaty was as much driven by political aims and concerns as the desire for economic gain from nuclear power. The treaty provisions reflect the priorities and conditions deemed necessary for the exploitation of nuclear power at that time. Under the treaty, the Euratom Commission (later the European Commission) acquired the status of a supranational regulatory authority for radiological protection, supply of nuclear fuel materials and nuclear safeguards.

The safeguards provisions reflected the US bilateral requirements, but gave Euratom direct responsibility for fulfilling security demands. Some aspects of the uniqueness of the safeguards arrangements are that they gave rights of inspection in all member states (including nuclear weapons states) through the provisions of Article 81 of the treaty – (inspection powers which are limited in the case of the IAEA). The defence clause of Article 84 exempts materials declared for military use from safeguards, and the Euratom treaty does not prohibit military use of materials by member states. Article 86 gives right of ownership of special fissile materials produced or imported to the Community.

3. Implementing Treaty Safeguards (Early Years)

A major task for the Commission following entry into force of the treaty was the enactment of legislation to define the safeguards requirements. In 1959 Euratom issued safeguards regulations (7 and 8). Regulation 7 specified the means for complying with Article 78 on declaration of operating characteristics of the installation for safeguards purposes, although initially debate centred on the application of this to defence establishments [5]. This issue was eventually settled in favour of the member state and gradually a uniform application of the rules was established. Regulation 8

defined the rules for accountancy, reporting of movements, material inventory and of inspection. Mid-1959 saw the start of monthly declarations of material movements by the facility operators. Initial visits to nuclear installations took place in the second half of 1959, and the first Euratom inspection took place at MOL in Belgium in April 1960. Regular inspections by nominated inspectors (initially a team of just 4 persons), followed from May 1960 as required by Regulation 8 [6].

As an indication of the type of facilities covered by the regulations at the end of 1959, it comprised: 49 active installations (9 research laboratories, 20 industrial facilities, and 20 mainly research reactors). Monthly figures on stocks and movement from these installations were being sent routinely to Euratom. By 1960 the Commission had gained sufficient experience that the USA accepted Euratom controls in such facilities as the sole control over nuclear material of American origin. Thus the Euratom safeguards system was established as the first regional as well as international operational safeguards system [5].

The growth in safeguarding activity in this early phase is shown in Figure 1 below, which shows the number of installations subject to Basic Technical Characteristics (BTC) declarations (regulation 7), the number subject to periodic reporting of material stocks and movements (regulation 8), and the number of inspections that took place.

In 1962, Euratom began approval of the chemical processing techniques and plant characteristics for three spent fuel reprocessing plants. The first, the Eurochemic project at MOL, Belgium commenced operation four years later [7]. In 1963, the operation of the first full scale industrial power reactor (in France) brought new challenges to safeguards. The expansion from research plants to full scale industrial

plants called on new techniques to cope with verification of bulk raw materials and uranium hexafluoride gas rather than just finished fuel elements [8]. Safeguards verification in the early days was mainly based on accountancy declarations, simple mass/volume measurements or sample taking, but research was on-going to develop new instrumentation and measurement techniques. The inspection regime at the reprocessing plant called for continuous inspector presence initially, the control measures requiring US and Canadian authorities' acceptance for material of such origin [9]. The number of inspections in the period 1960-1967 by installation type is shown in table 1.

Installation type	No of inspections
Fuel fabrication plants	101
Power reactors	53
Research reactors	177
Research centres	50
Irradiated fuel treatment	20
Fuel stores	10
Total	411

Table 1: Inspections by installation type 1960-1967

The quantities of imported material under Euratom safeguards are shown below, illustrating the early dependency on imports of mainly enriched uranium. With the advent of the new power reactors from the mid-1960's the quantities of nuclear material under safeguards control started to rise.
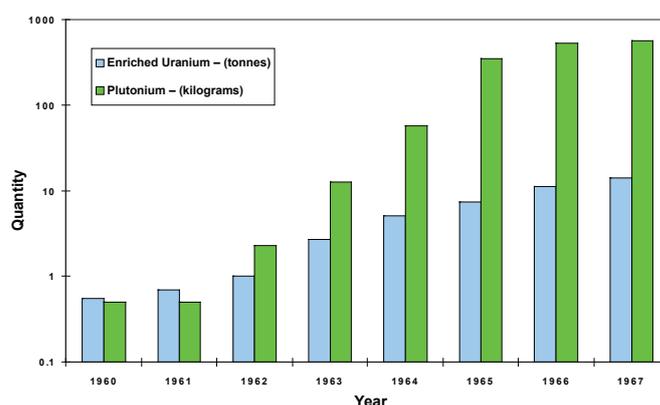
Figure 2: Imported Quantities of Material under Euratom Safeguards, 1960-1967
(high- and low-enriched U, and Pu)

4. Safeguards Development (Later Years)

The experience gained in these early years was of great importance for the future of Euratom safeguards. The late 1960's and early 1970's brought new challenges to Euratom treaty safeguards due to the negotiations for the Non-Proliferation Treaty (NPT).
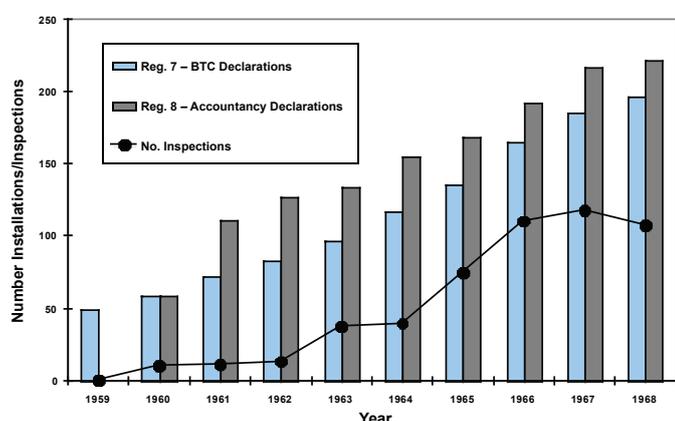
Figure 1: No of Installations subject to Regulations 7 and 8, and inspection level (1959-1968*).
(*Additional continuous inspections also took place in 1966-68).

Euratom's regional safeguards system came under severe challenge and risked being superseded by overriding international non-proliferation concerns. The desire to put global non-proliferation agreements in place put pressure on existing member states to accept IAEA safeguards in substitution for regional Euratom safeguards. Differences of view existed amongst member states, and further complications arose with the presence of the Nuclear Weapons States (NWS) initially France, and later the UK. Compromises had to be accepted that allowed both organisations to pursue their objectives in parallel. The INFCIRC 193 agreement defined the means by which IAEA would obtain independent verification of safeguards in the Non-Nuclear Weapons States (NNWS), whilst Euratom continued its regulatory role in the region. In the event, both NWS entered into voluntary agreements with the IAEA that allowed limited safeguards verification in their territory. The need for more formal agreements between the two organisations over the implementation of safeguards in the European community forced a redefinition of safeguards rules for accountancy, inventory change and material balance reporting. These were elaborated in the Community Regulation 3227/76, which was to remain the mainstay of Euratom safeguards regulation for the following 30 years.

In the early 1970's, nearly one third of the electricity production in Europe depended on oil [10]. The global oil crisis of 1973 drew attention to EuropÈs dependency on such limited resources. Nuclear power generation in the early 1970's began to show strong growth. The increase in nuclear facilities and the amounts of materials under safeguards can be demonstrated by the number of installations subject to safeguards and the quantities of material subject to Euratom control. Euratom responsibilities expanded further with the adhesion of key nuclear power countries, UK (1973), Spain (1985), and Austria, Sweden, Finland (1995). The effects of these events are described below.

4.1. Period 1969-1987

Table 2 below and Figure 3 show the rise in materials under safeguards control. The entry of the UK into the Community in 1973 resulted in a 50% increase in nuclear materials under safeguards control and a similar increase in inspection effort [11]. Further accessions in 1981 (Greece) and 1985 (Portugal, Spain) increased amounts under safeguards still further.

4.2. Period 1988-2006

Safeguards controls developed still further throughout this period with joint cooperation

Year	U-Nat	Enriched U	Pu
1969	12500 tonnes	16500 kg	950 kg
1970	13950	17146	1020
1971	13863	25461	1535
1972	15611	36635	1862

Table 2: Quantities of Material under Euratom Safeguards, 1969-1972
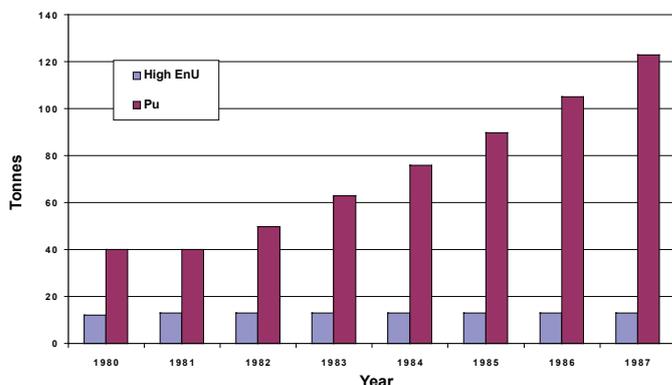
Figure 3: Quantities of Material under Euratom Safeguards, 1980-1987

agreements with the IAEA and new partnership approaches to rationalise still further the operations of the two organisations. Demand for nuclear power in Europe continued to rise, and this period saw inclusion of facilities in the new member states from 1995 (Austria, Finland, Sweden) under Euratom safeguards. The number of installations coming under safeguards control, as seen by the number of MBAs has continued to rise in this time, Figure 4. However inspection effort was dedicated to operations associated with higher risk. Currently, a major part (one third) of Euratom's inspection effort is dedicated to the reprocessing facilities at LaHague (France) and Sellafield (UK).
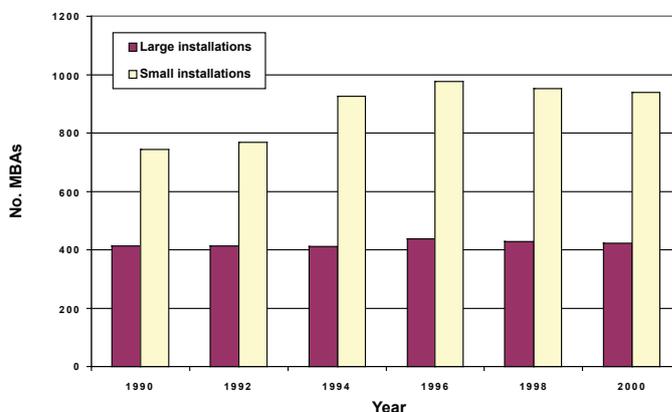
Figure 4: Number of Material Balance Areas (MBAs) 1990-2000

The equivalent quantity (as effective kg) under safeguards in the 10-year period from 1988 to 1998

increased by 188%, and in the ten year-period upto 2006, by 56%. This quantity is shown below in Figure 5.
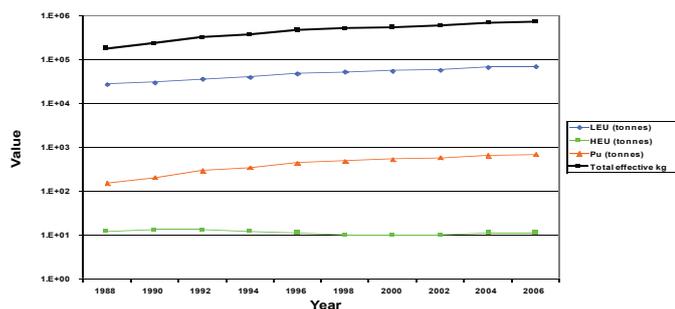
Figure 5: Quantity of nuclear materials under Euratom-safeguards between 1988 and 2006

The effect on inspection effort in the period to 1988-2006 is shown in Figure 6, demonstrating the effects of restructuring of Euratom inspection teams, and a policy toward reduced on-site inspection frequency.
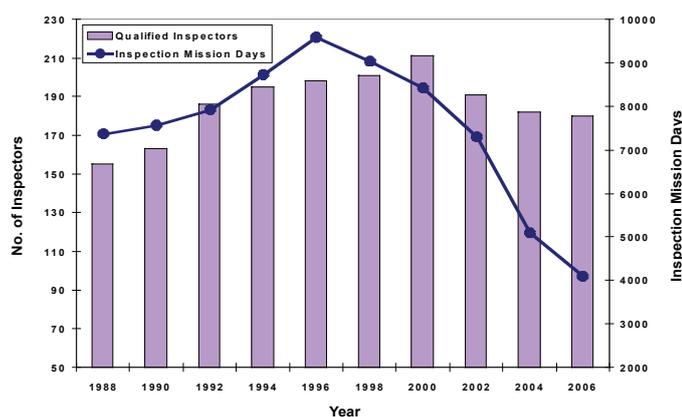
Figure 6: Inspection Statistics, 1988-2006

5. Review of Treaty Provisions

To meet safeguards objectives, the essential treaty requirements are stated simply in only 9 articles–(Articles 77-85) describing the essential features in a non-prescriptive, minimalist style. At its core are the basic functions to supply Basic Technical Characteristics (BTCs), provision of periodic operating and accountancy reports, and powers of on-site inspection. Although aspiring to community openness and transparency, member states were mindful of unwarranted intrusion in domestic and commercial affairs. It can be argued that a regulator should have greater rights to detailed information, and powers of scrutiny to fully assess the safeguards risks from the planning to execution stages of all nuclear projects. However, it can be said that this economy of regulation has been one of the reasons for the enduring nature of the regulations. The

compromise treaty wording that was found to be politically acceptable at that time, remains in place today and serves its function.

The treaty confers wide enforcement powers ranging from issue of a formal warning, withdrawal of technical or financial benefits, placing the undertaking under administration or ultimately confiscation of the source materials. This ability to apply enforcement action on the operator or the member state is unique amongst the safeguards treaties. As a regulatory body, the Commission has not been in-active in using powers of sanctions under the treaty when required. To demonstrate the regulatory actions of the Commission there are examples of sanctions taken against both member states and operators of installations. Euratom has taken legal action against a member state (one case-Article 82), issued formal warnings to operators (seven cases-Article 83), or placed the undertaking under temporary administration (one case-Article 83) [12].

Regarding its adaptability to changing circumstances, the treaty does allow for alteration to the procedures for applying safeguards, under conditions of unanimous agreement of the Council. Herein lies the enduring nature of the treaty, in that with 27 member states the consensus for change would be far harder now. However the call for change lies with a minority of member states.

6. Appraisal of Euratom Safeguards

The formative period of Euratom was no doubt a challenging and rewarding time for those who worked in the organisation. The work took place in a new field that promised to yield many benefits through the civilian exploitation of nuclear power. It required a mix of disciplines, and in an era of fast change and constant growth, demanded strong skills in collaboration and cooperation amongst the regulators, researchers and policy makers. Within a few years of its creation, Euratom could claim to be operating a comprehensive safeguards system, which managed to provide reassurance to all member states, both nuclear and non-nuclear power states, that safeguards obligations were being met in the installations in the community by their operators. That represents the first such system to operate within a collection of nation states.

European safeguards needs have provided a strong driver for research and development that has contributed to the safeguards needs internationally. The Joint Research Centres have contributed for example to develop, test, calibrate and validate

methodology, equipment and software for use by the inspectors, to train the staff in the technologies involved, and to support exploiting new technologies or approaches for both Euratom and IAEA. In the area of technical cooperation, Euratom and IAEA collaboration has been vital and yielded essential tools for common use. It can be said that the techniques developed through European research have application outside of nuclear controls. For example, it is thought that safeguards experience gained from control of civil nuclear materials can also be usefully applied to verification of nuclear weapons under the proposed Fissile Material Cut-Off Treaty [13].

The treaty provisions although developed at a time of 6 nation membership, has been adopted by 6 successive waves of accessions to the community, the most recent in 2007. Euratom successfully adapted to the demands of the nuclear power infrastructure of the new member states to the European community.

The value of inspection has been shown by their ability to detect discrepancies in operator records and declarations. These anomalies are subject to investigation and frequently are found to be due to isolated cases poor practice rather than systematic problems. In a very small number of cases operators have been found to be non-compliant and corrective actions requested. In some extreme cases legal action has been taken against the operator.

Controversy surrounds the benefits and successes of the treaty as a whole because of its origins as a pro-nuclear device. Many have criticised the Euratom treaty for the extent to which it has distorted the energy supply options in the last 50 years, and its relevance to current energy policy given the (uncertain) future of nuclear power. Regarding provision of economic aid for nuclear power, there is also some criticism of the lack of accountability to parliamentarians. All these are wider points worthy of debate, but it is worth noting that in the context of future energy policy, the same concerns about the stability of fossil fuel supply that existed in the fifties have remerged today.

Many argue that the commercial nuclear industry would have developed anyway – with or without the support of Euratom, however, the key feature of the treaty is that it made the development of nuclear power conditional on a strict system of safeguards. Most agree that concerning safeguards and the powers conferred by the treaty on the control of nuclear materials, the European Community has a good record and has played a vital role in the safe development of nuclear power. This achievement is not insignificant considering that the EU nuclear power industry has evolved to the point that it currently supplies 30% of its electricity needs. It is also one of the most highly developed commercial energy industries in the world, under strict regulations, providing a secure and reliable energy source that could not have been foreseen by the founders 50 years ago.

With regards to implementation of treaty safeguards provisions, some point to imperfections and possible lapses of control in the past. As is inevitable in the complex system of material handling and transport, there have been shortfalls in treaty compliance by operators and in the performance of the regulators. But it can be said that lessons have been learnt from these past lapses. The Euratom system of safeguards has provided reassurance to politicians, parliament and the public that strict controls do exist, operators are being carefully regulated, that obligations are being met. Given the political will and appropriate resources, much more could have, and can still be achieved here. Within a framework of regulation operators and member states recognise that Euratom safeguards serve an important function – primarily to serve as an audit of their practices to pinpoint deficiencies, and when needed to enforce strict application of the rules [14].

As in the case of nuclear safety – it is agreed that for the effective and safe development of nuclear power it is essential to have an independent, highly effective and powerful regulatory authority to oversee its operations. The management of safety or security critical operations requires a strong regulatory authority with the necessary technical and financial resources to provide a high level service. In this context it has been shown that a strict system of safeguards not only assures material control for the purposes of non-diversion, but contributes to safety controls and safety performance, given the overlap of interest in maintaining a strict system of assurance and knowledge of processes and materials.

However, the main success of the treaty lies in the degree of community integration engendered by the safeguards arrangements. The ability of nationals of one country to verify implementation of safeguards in another neighbouring country by accord contributes to the transparency and confidence for establishing security in the region. These principles first enacted in the EC have resonance with the NPT non-proliferation aims and from the post-cold war era the nuclear arms control and disarmament phases in world politics. The experience gained in developing structures, methodology, technical skills

and legal apparatus hold lessons for the other areas of arms control. It can be said that European safeguards control and monitoring – despite technical limitations, political interferences, complex relationships between members states, EU institutions, nuclear operators, and the IAEA–have achieved a major advance in international cooperation. The Euratom treaty can claim to have contributed to this achievement.

7. Strengthening Safeguards and Future Challenges

More recently the entire mission of the Euratom safeguards body has been questioned [15]. The non-proliferation remit and its selectivity (with reference to European weapons states) have been under scrutiny. In September 2000 a general discussion on the future of Euratom and its tasks was launched in relation to an internal reorganisation within the Commission framework. A High Level Experts Group (HLEG) was convened to make recommendations and in its report stated "….from a legal standpoint, Chapter VII…defines merely a nuclear material verification system under which accounting records, operating records and basic technical characteristics of facilities are properly kept by the facility operator and verified from time to time [by Euratom]." It is argued that excessive intrusion in operators' facilities is unnecessary since the non-proliferation aims are somewhat redundant in today's Europe, and that inspection regimes should be realigned to material security objectives. However, even this very critical overview of the safeguards function does not recommend a review of the treaty. The treaty remains relevant to current concerns – more so to do with security than non-proliferation.

It can be argued that the purpose of regulations is to confer some benefit, to provide clear rules about acceptability, and to describe a means for compliance, as well as operate as a deterrence against non-compliance. It is generally agreed that the Euratom system of control is well regarded by member states and operators. Current provisions are well accepted, well applied, and have provided confidence in the control of material in a period of rapid changes in the development of nuclear power. Concerning the issue that security of materials (against individual or group diversion) is the predominant risk, it could be argued that increased vigilance, and realignment of priorities is necessary rather than wholesale dismantling of treaty infra-structure.

However, as with all long established legal instruments, regular periodic review and redefinition of priorities is essential. It can be said that the Euratom safeguards authority (presently under DG-Energy and Transport) has been through a protracted period of introspection and scrutiny in recent years. What emerges is that the tasks of the organisation remain as important now as they were at any time in the last 50 years. Given that new threats exist today, it is of paramount importance that knowledge and expertise is maintained, that technical development continues, and that we do not become complacent to the inherent dangers in working with special nuclear materials.

In a climate of increased threats from loosely defined individuals and terrorist groups rather than through coordinated actions by nation states, the need for increased vigilance cannot be understated. To date, safeguards has only concerned itself with nuclear materials. However in the context of concern about the possible misuse of other materials – attention should also be focused on safeguards measures for all high risk radioactive material. More so now than ever before, there is merit in redundancy of checks and verifications at every level.

The question remains, how to maintain a system of regulation which achieves the main objectives of independent verification, without being too complex, unwieldy, and burdensome on the operators? Much has been discussed in the scope of new approaches, improved efficiency and changes to safeguards provisions, eg to allow transfer of data, audit techniques, the need to incorporate new technologies, the use of more targeted inspections, the importance of separation of the operator's responsibility from that of the regulator (putting the safeguard obligation back onto the operator). However, what the treaty demonstrates is that safeguards demands do not require overly complex regulations. Over the next 50 years, the nuclear industry will be increasingly involved in decommissioning activities. These tasks, as well as the need to deal with legacy items bring many challenges to operators and regulators – requiring greater flexibility of approach but rigid demonstration of compliance.

8. Conclusion

The origins and development of Euratom's mandate were difficult and at times controversial particularly as it has been and continues to be a heavily politicised issue. It is therefore all the more remarkable that despite political and institutional difficulties in the last 50 years, the original treaty

survives and its aims have been met. From very modest beginnings in the late 1950's, with a small core of staff and few facilities, European regional safeguards quickly established itself, and its expertise evolved to cope with one of the most advanced energy industries in the world. The figures show the rise in the quantities of nuclear material in use, representing the growth of the industry, and the large quantities under safeguards control today. The Euratom regional safeguards system continues to play an essential role in its regulation and control. For the demands and concerns of the European citizen, it can claim to be successfully serving its purpose.

However, decisions with respect to future contribution of nuclear energy are reaching an imperative stage. It is necessary to look at the treaty provisions critically and appraise the value of the regulations in relation not only to the future use of nuclear power, but on-going decommissioning liabilities which will extend to many years. It is clear that some treaty requirements could be amended or enhanced, for example shared decision making with parliamentary institutions would strengthen accountability and collective responsibility. Any amendment or translation of the treaty provision on safeguards should take account of forthcoming challenges. At a European level, the societal value of safeguards provided by Euratom should be reappraised, not least because the price to pay for even a single undetected real diversion would be beyond contemplation for the public.

The future development of nuclear power is a matter for the politicians and the public in each of the member states. For the service of the public, the supporting regulatory system must be able to provide an independent and trustworthy reassurance that safety and security aspects in the nuclear power industry are being treated with the importance they deserve.

Acknowledgement

Any opinions expressed in this paper are those of the authors and do not represent the official point of view of the European Commission.

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Multilateral nuclear arrangements: Status and outlook

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Please note, the following paper was previously presented at the 2007 ESARDA Symposium and therefore will also be published in the proceedings.

The concept of "multilateral nuclear arrangements" (MNA) has gained renewed attention as a way to strengthen the non-proliferation regime through the "de-nationalisation" of sensitive fuel cycle facilities in Non-nuclear Weapons States (NNWS). In early 2005, the IAEA Expert Group on MNAs reviewed the scope of such arrangements, from strengthened suppliers' assurances to the joint multinational construction of nuclear facilities. Since then, the IAEA has been the focus of serious discussions on a number of specific proposals for assurances of fuel supply to NNWS. Conversely, a number of countries have continued the development of their own national enrichment facilities, while others have expressed an interest in doing likewise, in particular uranium exporters eager to add value to their exports and to participate in the international supply market.

Assurance of supply for the operation of their nuclear power plants is the primary issue confronting NNWS, their first priority, ahead of general proliferation concerns. NNWS are unwilling to renounce their fundamental rights under the NPT (Non-Proliferation Treaty). Up to now, in spite of the small number of international enrichment suppliers – all connected to a NWS–the market of enrichment services has been fluid and mostly non-discriminatory. Nuclear plants operators in NNWS favour the continuation and the broadening of the present supply market.

Most MNA proposals come from supplying States: a voluntary commitment by a NNWS to forgo its own sensitive facilities would be exchanged against strong commitments to cover its fuel needs through supply-side commitments with or without IAEA involvement. What would be the incentives for a NNWS to enter into such arrangements? Economical, political? Should the internationalisation of sensitive nuclear facilities become the norm under the NPT?

The present paper deals with such questions from the perspective of small NNWS countries strongly dependent on nuclear energy for their economic and social welfare. How are the ambitious MNA schemes put forward in 2006-2007 in the name of non-proliferation to be reconciled with the deep concern of these countries to see their nuclear plants deprived of fuel through arbitrary and politically motivated supply restrictions? These "consumer countries" claim their own legitimate economic and political interests as fully "virtuous States" under the NPT. Economics is clearly in the foreground. Nonetheless, political considerations are not far behind, with genuine frustrations of seeing the nuclear weapons States unwilling to move an inch forward on the disarmament front (this year, refusing again to launch negotiations on a Fissile Material Cut-off Treaty in the frame of the Conference on Disarmament in Geneva).

The MNA Expert Group

In mid-2004, the IAEA brought together a group of 25 experts from the technical and diplomatic communities–with the mandate to identify issues and options relevant to multilateral approaches for both front and back ends of the nuclear fuel cycle, and to provide an overview of the policy, legal, security, economic, institutional and technological incentives and disincentives for cooperation in multilateral arrangements. Two primary deciding factors dominated the assessment of multilateral nuclear approaches, namely "*Assurance of supply and services*" and "*Assurance of non-proliferation*". Both are recognised overall objectives for governments and for the NPT community. History has shown that it is quite difficult to find an optimum arrangement that will satisfy both objectives at the same time.

Whether for uranium enrichment, fuel reprocessing, or spent fuel disposal and storage, MNA options span the whole spectrum–from existing market mechanisms, up to co-ownership:

Type I: Assurances of services not involving ownership of facilities:

a) Suppliers provide additional assurances of supply

b) International consortia of governments provide additional assurances

c) IAEA-related arrangements strengthen assurances

The focus is here on reinforcing existing commercial market mechanisms on a case-by-case basis through long-term contracts and transparent suppliers' arrangements with government backing. *Examples: fuel leasing and fuel take-back offers, commercial offers to store and dispose of spent fuel, as well as commercial fuel banks*. Also, in developing and implementing international supply guarantees with IAEA participation: *Different models to be investigated, notably with the IAEA as guarantor of service supplies, e.g. as administrator of a fuel bank.*

Type II: Conversion of existing national facilities to multinational facilities

Concept: Promoting voluntary conversion of existing facilities to MNAs, and pursuing them as confidence-building measures, with the participation of NPT non-nuclear- weapon States and nuclear-weapon States, and non-NPT States.

Type III: Construction of new joint facilities

Objective: Creating, through voluntary agreements and contracts, multinational, and in particular regional MNAs for new facilities based on joint ownership, drawing rights or co-management for front-end and back-end nuclear facilities, such as uranium enrichment; fuel reprocessing; disposal and storage of spent fuel (and combinations thereof).

In its report of February 2005[2], the Group concluded that MNAs offer a potentially useful contribution to meeting prevailing concerns about assurances of supply and non-proliferation.

Follow-up proposals

Since the publication of the IAEA Expert Group report, a number of proposals concerning *only* Type I have been tabled and extensively discussed.

USA: Global Nuclear Energy Partnership (GNEP)

In February 2006, the US Government announced the launch of a "Global Nuclear Energy Partnership", an initiative[3] with very positive and far-reaching proposals, such as the expansion of nuclear power in the US, the development of advanced nuclear fuel cycles (including reprocessing), or the stockpile

reduction of separated civilian plutonium. On the negative side, under the flag of non-proliferation, the GNEP would confine drastically the fuel service market. The USA, UK, France, Russia, China (and Japan?) would be "*Fuel Cycle Nations*" providing nuclear fuel to others (the "*Reactor Nations*")–in exchange for the commitment to forgo enrichment and reprocessing activities. A fuel-leasing plan envisages supplying enriched fuel for initial use in customer countries to be followed by its return, by chemical separation and by the burning of recycled materials in the "Fuel Cycle Nations". In a nutshell, the key elements of the civilian nuclear fuel (enrichment and reprocessing) would be fenced off and kept in the hands of Nuclear Weapons States running a kind of cartel. The man-made energy resource – plutonium – would flow to and be kept in the Fuel Cycle Nations and benefit only them.

GNEP is in essence a denial of technology based on the national policies and priorities of weapons States, but shrouded in well-meant non-proliferation principles. Some rare "reactor nations" – or more to the point, "consumer countries" – may well voluntarily consider such a proposal if attractive technologies and economic incentives are offered to them in exchange for renouncing national fuel cycle facilities. Time will tell – in a decade or so.

Uranium enrichment industry

In May 2006, the World Nuclear Association (WNA) published a report[4] representing the views of a 28-member panel of nuclear industry experts regarding an industry-based backup supply mechanism.

The report tries to tackle the problem at hand through an unwieldy mixture of economical and political considerations that fail to take into account the interests of customer countries. Quite correctly, WNA states that any approach to strengthening security of supply should be consistent with the continued effective operation of the competitive world market and that any arrangement for emergency or backup or guarantee supply arrangements should be used only as a last resort when existing market arrangements have failed, and not as a substitute for market supplies. Unsurprisingly the uranium industry wants "*no price discrimination against supplies from the normal market, and hence no price subsidies for the emergency or backup or guarantee supply arrangements*". In truth, rather than receiving subsidies, the customers should – it seems–pay a premium for such guaranteed supply arrangements! Unfortunately, WNA supports the political string that would be attached to such arrangements ("*To be eligible, a customer State*

must have made a commitment to forego the development of, or the building or operation of, enrichment facilities"). Confronted with such a special "non-competition" clause, the customer countries will of course not pay a premium; they will not even consider such a restrictive arrangement without substantial economical incentives. Since the enrichers also want to be somehow compensated for the cost of providing such guarantees (e.g. dedication of inventory, construction of facilities, and actual supply costs), the proposed industrial arrangements will for sure require an ample source of third-party funding to satisfy financially both enrichers and customers.

The Six-Country proposal

In June 2006, six countries with commercial uranium enrichment activities – US, UK, France, Germany, Netherlands and Russian Federation, tabled a proposal[5] to offer 'reliable access' to nuclear fuel for States opting to rely on the international market for nuclear fuel and not to have domestic enrichment activities. Further conditions of admission are to be ascertained by the IAEA: to have a comprehensive safeguards agreement and an additional protocol in force, and to have no exceptional safeguards implementation issues outstanding with the Agency (in other words, the kind of countries having already a reliable access to the market…). The proposal refers to suppliers arrangements, to fuel reserves and to a limited broker role for the IAEA. There is no visible incentive for the customer countries, except the intent to consult them and a reassuring declaration of non-discrimination against the non-takers ("*Conditions of access to the commercial market for enriched uranium will not be affected for Recipient States that do not participate in this mechanism*").

Japan: standby assurance

In September 2006, Japan proposed to establish a system[6] called the "*IAEA Standby Arrangements System for the Assurance of Nuclear Fuel Supply*" under IAEA auspices, that incorporates both an information system to contribute to the prevention of the occurrence of market failures and a back-up feature for supply assurance proposed in the Six-Country proposal[7]. This was a limited, but valuable proposal.

UK: Enrichment bond

In September 2006, the United Kingdom, in the context of the supply assurance envisaged in the Six-Country scheme, proposed[8] an "Enrichment Bond". This would enable "prior consent or de-flagging" for provision of enrichment services through the IAEA for qualifying recipient States. Germany and the Netherlands have associated themselves with this initiative. This means that the uranium suppliers will provide "*advance assurances that export approvals will be granted*" for further supply through the IAEA. Such a bond is of a major importance, since it lends the needed credibility to any IAEA-sponsored arrangement. Other suppliers of uranium or fuel services still need to express their readiness to accept such a scheme.

IAEA fuel reserve

Also in September 2006, the "Nuclear Threat Initiative" (NTI) – a US non-governmental organisation–proposed to set up a stockpile of low-enriched uranium under the Agency's auspices to serve as a last-resort fuel reserve for countries that have elected not to build a national uranium enrichment programme[9]. NTI offered a challenge grant of US$ 50 million to be matched by US$ 100 million to be raised by the IAEA and its Member-States (in funds or in nuclear material). On May 23, 2007, the US House Foreign Affairs Committee approved a bill that authorises $50 million toward the same fuel bank initiative (as part of the $100 million matching amount). The IAEA is expected to develop the modalities of such a fuel reserve as to its technical and legal dimensions[10] (in particular as to qualifying criteria and release criteria).

International enrichment centres

Again in September 2006, Germany proposed the creation of an international uranium enrichment facility–operated by the IAEA at an extraterritorial (international) site[11]. The enrichment plant would be built as a "black box" and would only be accessed and maintained by the technology supplier. The plant would be built and operated on a purely commercial basis, without IAEA subsidies. This is a sensible but ambitious proposal. The advantages in terms of economics and non-proliferation are not evident, when this option is compared to the IAEA fuel bank concept fed from existing commercial nuclear facilities, since the release criteria would be practically identical.

Last October, Russia declassified the Angarsk enrichment facility and since then promotes it as International Centre under the IAEA[12,13]. There seems to be little difference with the EURODIF model that saw in the seventies a number of countries (Italy, Spain, Belgium and Iran) invest in the plant construction in exchange for assured fuel deliveries,

but without access to the technology. The possible involvement of the IAEA is not convincing, since there is not much more "internationalisation" than under EURODIF. Nonetheless, Russia would welcome international investors to help expanding the facility. Will there be an ironclad assurance of delivery–in the light of Russia's inclination to flex its energy muscle occasionally?

Last, but still to be mentioned, Iran has suggested on various occasions the joint construction and operation of a multinational enrichment facility on Iranian soil. This is not likely to happen soon in view of the low level of international confidence in Iran's declarations. With the current obsolete centrifuge technology tested in Iran, nobody would *care*. With a more modern technology, nobody would *dare* for a very long time.

The academic world has also put forward some interesting ideas, including concepts that would combine assurances of supply with insurance and financing arrangements, a mix that could possibly provide economical incentives for customer countries to participate[14].

Qualifying criteria – release criteria

Who would qualify to "benefit" as a customer country from the various proposals put forward? The common condition is that the country should renounce any plan to build a sensitive enrichment or reprocessing facility on its territory, not even – it seems–in a regional or international framework. This being apparently not enough, all schemes of assurances of supply start with the proviso: …"*provided the State is in good standing with the IAEA*", a short sentence that for some people should go as far as piling up all the desirable features: 1) a comprehensive safeguards agreement of course, 2) a ratified and implemented additional protocol, 3) good track records in nuclear safety and security, 4) implementation of the United Nations Security Council Resolution 1540 on the non-proliferation of weapons of mass destruction and 5) solid nuclear export controls. For the most demanding pundits, the qualifying examination should include as well political/strategic considerations and the rationality of nuclear energy choices. *This goes too far; this is the best way to defeat the whole undertaking*. States fulfilling all these conditions will buy without restrictions whatever they want from the market and they will even build unhampered their own enrichment facility if they so wish on economic grounds. In order to attract less virtuous countries, the ladder should be set lower, as low as requiring only the first and third conditions here above. The same should apply

to the release criteria to be adopted by an IAEA fuel bank or other international schemes.

Waiting for customer countries

During the Special Event of the 2006 IAEA General Conference, a representative of the US government presented an impressive list of very good questions to address about each and all of the above proposals[15]. Still, he failed to ask the critical question, the essential issue to be investigated: "*How to make these proposal palatable to large and small non-nuclear weapons States in good standing – and even more important, to those that are not?*"

Without a doubt, finely chiselled schemes have been elaborated by nuclear industry, by fuel cycle States and by and for the IAEA under the heading "assurances of supply" – all apparently to the benefit of States ready to renounce domestic sensitive facilities. Where are the grateful guests? They are not yet at the door.

- States in good standing will not show interest for a long time in such complex arrangements of unproven value; they will stick to the open market (…and they will not be denied supplies). With a functioning market enlarged with the participation of additional suppliers, the customer countries will most likely eschew complicated fuel bank schemes managed by the IAEA; they will not give up the rights enshrined in the NPT.

- States not in good standing will not even come to the door unless *pulled* or *pushed* towards MNA schemes. Economical and other incentives (even possibly subsidised fuel) should indeed be devised to attract such consumer countries to MNA solutions. In the context of graded penalising measures following violations, measures decided by the Board, one can also imagine pushing non-compliant States towards MNA.

Nuclear weapons States have nothing to loose on assurances of supply with their large and closed fuel cycles. The NNWS, it's different: they must always learn at their own risk to balance cautiously their vital energy needs and their interest in non-proliferation. In the on-going MNA debate, the NNWS customer countries will listen, they should also make their own position heard more loudly, but they still need to be convinced on the need for sweeping MNAs.

In essence, the NNWS want a competitive nuclear market in which low-enriched uranium would be a "commodity" under stringent safeguards, but widely available from many sources, and in which plutonium recycle would remain an open option for nuclear

power operators. Is this view compatible with non-proliferation objectives? In principle, yes.

Nonetheless, with both objectives in mind – more nuclear power and stronger non-proliferation for the world – the nuclear community at large must imperatively readjust its plans and its vision in order to ensure a smooth development of nuclear power. The number of enrichment and reprocessing facilities <u>cannot</u> expand in proportion to the number of nuclear plants. Therefore, the likely scenario of a strong expansion of nuclear energy around the world calls for the development of nuclear fuel cycles with stronger multilateral arrangements – by region, by continent or by dedicated cooperation. Ancillary, but essential: Such multilateral facilities should not all be located in nuclear weapons States, so as to provide as much supply diversity as possible to those plant operators in non-nuclear weapon States with a vital dependence on nuclear power.

Schemes on assurance of supply and fuel banks (Type I) are unlikely to attract more than a handful of customer countries. The conversion of existing sensitive facilities into genuine international undertakings (Type II) meets with difficulties for the participating countries (obsolescence, national interest, security, safeguards implementation, financial and political risks). Of much greater importance are future facilities for which Type III schemes are the real solution. In NWS and in NNWS, multinational facilities should become the norm when a country, a region, a continent wants its own enrichment supply. South America, Japan and South Korea together, Australia and Canada together (as potential suppliers of enrichment services) and possibly small European countries together.

Such multilateral solutions have economical, commercial and political advantages. As such, they would not hamper the development of nuclear power, while undoubtedly strengthening the non-proliferation regime.

A suite of ten considerations

As pointed out by Harald Müller[16] from the Peace Research Institute Frankfurt, all MNA schemes have been developed as "national supplier policies" without much consideration for consumer countries, giving an impression of discrimination between "haves" and "have-nots" bound to exacerbate antagonisms. Using the same terms, the former Director General of the IAEA, Hans Blix, noted recently in Berne that the NPT freezes the "haves" and "have-nots" in the possession of nuclear weapons; and that now the "virtuous countries"

should accept to hand over the possession of the civilian fuel cycle to the same "haves".

The basic question is indeed the one raised by Chaim Braun[17] from Stanford University: "Who is interested in implementing supply assurance proposals: the suppliers or the prospective users?" So far, only the supplier countries have spoken, while the consumer countries keep quiet, satisfied by the world market for fuel services and not yet ready to engage in restrictive practices without the offer of proper economical and political incentives.

Where do the customer countries – and in particular the customer utilities operating nuclear power plants–stand on the rich display of MNA proposals? Impossible to say yet; however, the following considerations may be worthwhile keeping in mind:

1. Small nuclear power plant operators located in small countries want a fluid and competitive market. Today, the commercial market satisfies the demand for fuel services; there is a diversity of commercial enrichment companies; enrichment capacity exceeds demand; and, based on current plans for the substitution of diffusion by centrifugation, capacity is likely to comfortably keep abreast of projected increases in demand in the medium term (e.g. until the end of the US/Russia agreement on HEU conversion to LEU). For other front end processes (such as conversion and fuel fabrication), the situation is similar.

2. The dependency on only a few enrichment suppliers located in and controlled by nuclear weapon States gives rise to concerns as to the continuity in the assurances of supply. Customer countries would welcome a greater diversity in fuel services and would welcome newcomers like Australia and Canada, countries that are already major players and reliable partners on the uranium scene.

3. Furthermore, to achieve an even more competitive fuel cycle market, the purchasers of nuclear fuel should seek a complete liberalisation of the market–with more suppliers–to achieve a perfect fluidity of supply. For example, this could be achieved through a "Commodisation of enriched uranium", the setting up of a kind of international "Chicago Commodity Market" for uranium dioxide, with twin entries: a low-value product at the natural 0.7% enrichment level and a high-value product at a maximum of 5%, each with a long-term market and a spot market. Physical mixing would provide the required enrichment just prior to fuel rod fabrication. Low-enriched uranium as a commodity can be easily

stockpiled in a customer country or in a pool or cooperative of customer utilities.

4. As far as fuel element fabrication is concerned, there is no proliferation concern since fuel fabrication plants are not sensitive. Therefore, no need for ambitious international schemes. From a utility standpoint, as many such plants as possible in as many countries as possible makes sense. Group of countries or existing economic organisations (such as OECD) should see to it that a flexible and adequate fabrication capacity is always available for their own assurance of supply.

5. The overwhelming majority of consumer countries would probably be ready to renounce building *purely national* sensitive facilities, but not ready to give up the right to do so *multilaterally* with partners of their choice. For enrichment and reprocessing, they want to keep their commercial freedom to build such facilities jointly with like-minded (if it makes economic sense). Furthermore, they consider plutonium as a potential resource for their own good, with no inclination to leave that privilege to a few leading countries.

6. The issue of new multilateral facilities should indeed be addressed at the 2010 NPT Review Conference. Short of an impossible treaty amendment, as part of a broader bargain between NWS and NNWS, the Review Conference should decide that future sensitive facilities are to be built in an appropriate multilateral or regional framework.

7. All other proposals (from the GNEP to international fuel centres) should be for a while kept out of the broader proliferation agenda and pursued separately on their own merits, as complementary measures to the open market. On the one hand, a number of consumer countries may well be interested in such incremental supply guarantees. On the other hand, supplier countries may be ready to offer attractive conditions to consumer countries willing to give up their own sensitive fuel cycle facilities. Let the two sides negotiate the proper terms in a series of bilateral arrangements, without attempting to create an all-encompassing framework under the NPT or in association with the IAEA. Experience over time will show those schemes most suitable for various partners, and, may be, some of them could later become worthwhile of consideration in the NPT context.

8. All the supplier-side proposals summarised above suffer from the same fundamental weakness, namely the lack of economic incentives. If the consumer countries are to come to the table, the promoters should do more than claiming noble non-proliferation aspirations. Substantial benefits in the form of price rebates or long-term economic clauses should be offered to the plant operators in order to entice their government to accept broader political constraints on industrial nuclear development for enrichment and reprocessing.

9. All IAEA related proposals (fuel banks and fuel centres) are confronted to diverging perceptions about the political independence of the IAEA. Over the years, the IAEA Board of Governors has functioned smoothly and efficiently when compared to other international bodies plagued by size and veto rights. Yet, the Board is eminently political, not always free from external pressures. An influential Board member – after having denied a fuel delivery – will do its utmost in the Board to prevent the IAEA to step on the scene as a substitute supplier. To give the IAEA a maximum of credibility for any of the proposals put forward, a clear distinction must be made between the role of the Board and the role of the Secretariat. It is up to the Board to write the appropriate guidelines and up to the Secretariat to implement them free from external interferences.

Thus, a new major role for the IAEA requires two essential pre-conditions:

• The delegation by the Board of Governors to the Secretariat of the operating competence for the implementation of "qualifying and release criteria" in relation to any fuel cycle activity of the Agency;

• The granting to the IAEA of a generic "prior consent or 'de-flagging' by the suppliers contributing fuel to the IAEA facility, in other words, the recognition of the IAEA as end-user.

In a word, consumer countries are unlikely to consider doing business with the IAEA, if the Secretariat and the Director General are seen or perceived exposed to the double interference, that of the Board members and that of the suppliers delivering fuel or raw materials to the IAEA.

10. Before getting bogged down in the planning of administrative and technical details, it seems advisable to gauge the reasons for consumer

countries to receive fuel from the IAEA, and to define incentives for them to do so. Dealing with the IAEA will imply a political risk for some (of having, so-to-speak, to "negotiate" with the 35 States represented on the Board, instead of one…), a risk that deserves compensation if an irreversible industrial and political commitment is expected from the consumer countries. How will these incentives depend on the non-proliferation credentials of the consumer country? Proportional or inversely proportional between a mere comprehensive safeguards agreement and a post-additional protocol "integrated clean bill of health". At any rate, in one form or another, incentives will be required.

Concluding remarks

During the IAEA Special Event of September 2006, many NNWS expressed scepticism and concerns about the proposed MNA schemes.

The Minister of Minerals and Energy from South Africa, Ms. Buyelwa Sonjica, summarised[18] most eloquently the views of NNWS: "… *there is a need to guard against actions, which would merely serve to exacerbate existing inequalities, including through the creation of another kind of cartel that would exclude full participation, particularly by States in full compliance with their safeguards obligations … Although prevailing proliferation concerns may prompt us to consider alternative arrangements on supply mechanisms, these may under no circumstances impose unwarranted restrictions and controls over the legitimate peaceful use of nuclear energy … If we agree to such conditions, we may well be contributing to undermining the very bargains on which the NPT was founded and further disturb the delicate balance of rights and obligations under this instrument … In addition, we should guard against the notion that sensitive technologies are safe in the hands of some, but pose a risk when others have access to them*".

The chairman of the event, Charles Curtis, concluded the meeting with some sober observations[19]:

"… *establishing a fully-developed, multilateral framework that is equitable and accessible to all users of nuclear energy, acting in accordance with agreed nuclear non-proliferation norms, will be a complex endeavour that would likely require a progressively phased approach…Other unresolved key issues are how to structure assurance mechanisms in a manner that does not result in a real or perceived division between nuclear fuel/reactor technology haves and have-nots, and does not undermine existing multilateral, treaty-based nuclear non-proliferation norms or State sovereignty/rights*".

This is why it would be wiser to set aside the "*fully-developed multilateral framework*". This is not only very complex, but even impossible to achieve if treaty-based nuclear non-proliferation norms and State rights are to be respected. A gradual and loose strategy is the only way to go: firstly, by making attractive for the consumer countries all these various proposals of assurances of supply, and secondly by focusing the broad political ambition to a single significant objective, namely, making multilateral arrangements the norm for all future sensitive nuclear facilities. On the first point, the sponsors should implement near-term projects with candidate countries to demonstrate their feasibility and attractiveness. On the second point, the non-proliferation community should work towards the 2010 Review Conference; if not possible there, it should seek a majority vote in the IAEA General Conference.

A recent (non)-paper from the European Union[20] has very correctly noted: "*As different States will have different motivations and interests, we should refrain from focusing on the idea of a uniform approach. A certain flexibility, taking into account the different national viewpoints, seems to be necessary. A step forward could be a mix of a limited number of multilateral mechanisms*".

The IAEA is going in the same directions. On June 15, 2007, commenting on the submission to the Board of Governors of a yet unpublished report[21], the IAEA Director General stated, "*Trends clearly point to the need for developing a new multilateral framework for the nuclear fuel cycle. And it´s clear that an incremental approach, with multiple assurances in place, is the way to move forward … Such a framework is voluntary and States are free to choose their fuel options–no rights of States would be compromised*".

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Automated extraction of change information from multispectral satellite imagery

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Abstract

Seeing the expected technical improvements as to the spatial and spectral resolution, satellite imagery could more and more provide a basis for complex information systems for recognizing and monitoring even small-scale and short-term structural features of interests within nuclear facilities, for instance construction of buildings, plant expansion, changes of the operational status, underground activities etc. The analysis of large volumes of multisensor satellite data will then definitely require a high degree of automation for (pre-) processing, analysis and interpretation in order to extract the features of interest. Against this background, the present paper focuses on the automated extraction of change information from multispectral satellite imagery

Keywords: change detection; change analysis; pixel-based techniques; object-based approaches; automation, high-resolution multispectral satellite imagery; nuclear safeguards purposes;

1. Background

Besides reviewing the "correctness", also the evaluation of the "completeness" of the State declarations has become a key issue within the safeguards system of the International Atomic Energy Agency (IAEA) today. The efforts for strengthening IAEA safeguards involve the implementation of various technical capabilities for verifying the absence of nuclear material diversion and undeclared nuclear material and activities. One of the technologies to be considered under the Additional Protocol and Integrated Safeguards respectively is remote sensing by commercial earth observation satellites.

In general, satellite imagery data and analysis represent an efficient and cost-effective open source of information for safeguards-related activities, such as verification, evaluation, investigation and operational support. In the absence of on-site inspections or environmental sampling, commercial remote sensing data provide one of the few opportunities to gather almost real-time data and thus information for the area of interest. The potential of commercial satellite imagery for strengthening IAEA safeguards has been effactually demonstrated in a number of case studies using date from the panchromatic, multispectral, hyperspectral and radar domain in the last years [1]. However, satellite imagery is far from being sufficient to solely confirm the existence or absence of nuclear activities.

For future NPT verifications tasks, however, both the number and area of sites monitored by satellite imagery data and the time intervals for observations are expected to increase permanently. From a remote sensing perspective, the technical developments in sensor technology led to improvements as to spatial, spectral and temporal resolution. The next generation of high-resolution multispectral satellite sensors (i.e. GeoEye, WorldView) will come along with an enhanced spatial resolution of 50 cm or even better. With the future radar satellites, such as TerraSAR-X, providing high spatial resolution of 1 to 2m image data from the microwave spectral domain will also become relevant for safeguards applications. Taking this into account, the amount of data in the image archives of the IAEA will consequently accumulate more and more.

Due to the fact that more data also involves a higher effort regarding image (pre-) processing, change detection, analysis and interpretation, computer-based techniques could be of great value in this respect. The image analysts could highly benefit from (semi-) automation and transferability of digital image processing steps in order to extract and utilise significant change information. Against this background, the present paper focuses on the automated extraction of change information from multispectral satellite imagery. In the following we give a short review on the state-of-the-art of automated change detection techniques and then

demonstrate and discuss some automated procedures for nuclear safeguards purposes.

2. Change detection

Change detection is the process of identifying and quantifying temporal differences in the state of an object or phenomenon [2]. When using satellite imagery from two acquisition times, each image pixel or object from the first time will be compared with the corresponding pixel or object from the second time in order to derive the degree of change between the two times. Most commonly, differences in radiance values are taken as a measure of change.

A variety of digital change detection techniques has been developed in the past three decades. Basically, the different algorithms can be grouped into the following categories: algebra (differencing, rationing, regression), change vector analysis, transformation (e.g. principal component analysis, multivarite alteration detection, Chi-square transformation), classification (post-classification comparison, unsupervised change detection, expectation-maximization algorithm) and hybrid methods. Reviews on the most commonly used techniques are given by i.e. [2,3,4,5]

Many of the algorithms used for analyzing temporal changes are indeed not restricted to change detection. In summary, there is a wide variety of alternatives having varying degrees of flexibility availability and significance, and only a few studies have been carried out for quantitatively assessing the different methods for one case study [6,7,8].

3. Data Pre-Processing

Differences in radiance values indicating significant ("real") changes have to be larger compared to radiance changes due to other factors [2]. The aim of pre-processing is therefore to correct the radiance differences caused by variations in solar illumination, atmospheric conditions and sensor performance and geometric distortion respectively.

3.1. Geometric Correction

A precise image registration is essential for an exact pixel-by-pixel or object-by-object comparison during the change detection process. By means of geometric correction algorithms, the image data can be registered to each other (image-to-image registration) or to a given map projection (georeferencing). In order to avoid false alarm signals due to misregistration effects, the procedure should be carried out at a sub-pixel accuracy level, i.e. with a RMS error well below +/- 1 pixel.

The registration of two data sets usually involves the selection of so-called Ground Control Points (GCPs) and Tie Points (TPs) in both images. Even though some standard remote sensing software systems offer an automation of the process to a certain extent today, the very time-consuming setting of GCPs still has to be done manually there. However, some techniques have been proposed for the (semi-)automatic determination of GCPs using for example Hough transform [9], Laplacian-of-Gaussian filtering [10] or image correlation [11].

For high-resolution imagery, the sensor's off-nadir viewing rather necessitates an orthorectifying procedure to remove sensor and terrain-related distortions. The orthorectification implies the existence of GCPs, the appropriate sensor model and a high-resolution digital elevation model (DEM). Elevation information can always be derived from satellite-based high resolution stereo image pairs [12,13] unfortunately stereo data is available either selectively in the archives of the data providers or on demand at a high price.

3.2. Atmospheric Correction

Radiometric correction procedures aim to calculate the absolute surface radiance or reflectance by removing the atmospheric effects. A comprehensive correction scheme by modelling the atmospheric conditions during image acquisition based on a radiative transfer code implies the knowledge of the atmospheric parameters at that time. Information on the precise atmospheric properties is not easily available, and using standard atmospheric models instead may result in a non-satisfactory correction.

For change detection applications of satellite imagery, absolute atmospheric modelling is rarely necessarily needed, and this applies to nuclear safeguards applications, too. Assuming that the relationship between the at-sensor radiances measured at two different times can be approximated by linear functions, a relative radiometric normalization seems to be sufficient here.

The different methods introduced in the literature [14] differ regarding the time-invariant features used as the basis for normalisation, e.g. pseudo-invariant features [15] or no-change pixels [16].

4. Pixel-based change detection

For the detection of changes on a pixel basis, several statistical techniques exist, calculating e.g. the spectral or texture pixel values, estimating the change of transformed pixel values or identifying the change of class memberships of the pixels.

In regard to the specific application of nuclear monitoring the most satisfactory results were carried out by the so-called Multivariate Alteration Detection (MAD) transformation [17]. The MAD procedure is based on a classical statistical transformation referred to as canonical correlation analysis to enhance the change information in the difference images and briefly described as follows: If multispectral images of a scene acquired at times t_1 and t_2 are represented by random vectors **X** and **Y**, which are assumed to be multivariate normally distributed, the difference D between the images is calculated by $D=a^TX–b^TY$.

Analogously to the principal component transformation, the vectors a and b are sought subject to the condition that the variance of D is maximized and subject to the constraints that var(a^TX)=var(b^TY)=1. As a consequence, the difference image D contains the maximum spread in its pixel intensities and -provided that this spread is due to real changes between t_1 and t_2– therefore maximum change information. Determining the vectors a and b that way is a standard statistical procedure which amounts the so-called generalised eigenvalue problem. For a given number of bands N, the procedure returns N eigenvalues, N pairs of eigenvectors and N orthogonal (uncorrelated) difference images, referred to as to the MAD variates.

Since relevant changes of man-made structures will generally be uncorrelated with seasonal vegetation changes or statistic image noise, they expectedly concentrate in the higher order components (if sorted according to the increasing variance). Furthermore, the calculations involved are invariant under affine transformation of the original image data. Assuming that changes in the overall atmospheric conditions or in sensor calibrations are approximately equivalent to affine transformations of the pixel intensities, the method is insensitive to both of these effects.

The decision thresholds for the change pixels could be set by standard deviations of the mean for each MAD or MAF/MAD component. Regarding automation a probability mixture model proposed by [18,19] was applied to the MAD or MAF/MAD variates. The techniques is based on an Expectation-Maximization algorithm to determine automatically the density functions for the change and no-change pixels and thence the optimal decision thresholds for discriminating change and no-change pixels.

The application and expressiveness of the proposed procedure depends (among other things) on the spatial resolution of the imagery. When a change signal within nuclear sites is very significant in terms of radiance changes, it can mostly be detected by the pixel-based analysis of mid-resolution multispectral image data. But when adopted to (spatial) high-resolution imagery, the results of the pixel-based algorithms are often limited. Especially if small structural changes are to be detected, object-based procedures seem to be advantageous. In comparison to the purely spectral-based features used within the pixel- based approaches, the inclusion of features such as the size or orientation of an object, its shape or texture and its relations to other objects on the same or at different scales, considerably extends the possibilities for image analysis.

5.   Object-based change detection

Computer driven, object-based image analysis is in a first approximation comparable to visual perception. An image interpreter recognizes, along with the colour of an image, also the shapes, textures and coherent regions present within it, and associates meaningful objects and their contextual relations. A similar goal is intended in object-based image analysis, although the complexity and effectiveness of human perception is of course far from being achieved. The extraction of the objects from the analysed image occurs at the lowest level by segmentation, at which stage the primary segments should ideally represent the real world objects. The feature analysis provides the basis for the preparation of a ruled-based classification model resulting in a classified image.

Analysing satellite image data in an object-based way generally extends the possibilities to detect changes between two or more dates. In addition to the change pixel measures listed before, object-based change detection techniques can also estimate the changes of the mean object , such as shape and size, assess the modified relations among neighboring, sub- and super-objects and find out changes regarding the object class memberships. Moreover, specific knowledge can be easily involved into the procedure.

Previous studies implying a combination of pixel- and object-based techniques have already demonstrated the advantages of firstly pinpointing the significant change pixels by statistical change detection and subsequently post-classifying the changes by means of a semantic model of change-related object features [20,21]. The software solution for an object-based image analysis is currently given by Definiens Professional [22].

5.1 Object extraction

Given Definiens Professional, the so-called multiresolution segmentation uses homogeneity criteria based on spectral and/or spatial information and a scale parameter in combination with local and global optimization techniques. For image data of two acquisition times, the segmentation into object primitives could be carried out a) on the basis of the bitemporal data set, b) by applying the segmentation parameters to the image data of one date and assigning the object borders to the image data of the other date, c) separately for the two times. When using a common segmentation (a, b), the generated objects show object features, which are either apparently time-invariant, such as shape, or differ at the two dates, i.e. most of the layer values. Thus, the time-variant object features present the basis to detect changes of and within the objects between the two dates. Provided a separate segmentation (c) for the two scenes, also the shape features will vary in time.

5.2 Feature extraction

Feature recognition is an essential part of object-based image analysis. A comprehensive feature extraction methodology is the precondition for successful work with image objects. Given the large number of possible features for object description, it is necessary to identify the characteristic, significant features for object-classes of interest. In order to avoid the time-consuming ``trial-and-error'' practice while seeking for significant class separating object features approaches towards an automatic feature extraction were used.

In the given project the optimal object features and the range of its membership functions were automatically determined by the feature analyzing tool SEaTH (SEparability and THresholds) [23,24]. The feature analyzing tool SEaTH identifies the relevant features with a statistical approach based on training objects. The statistical measure for determining the representative features for each object class is the pairwise separability of the object classes among each other. Subsequently, SEaTH calculates the thresholds which allow the *maximum* separability in the chosen features.

6. Application to bi-temporal multispectral imagery

The proposed procedure will be illustrated for a bitemporal, high-resolution satellite imagery considering as an example monitoring the Nuclear Fuel Research and Production Center (NFRPC) Esfahan in the Iran. NFRPC is Iran's largest nuclear research centre, built in 1974 in the south-east of the city of Esfahan. It operates two research reactors, a critical assembly and a sub-critical assembly. It also operates conversion facility, fuel production plant, a zirconium production plant, and other facilities and laboratories. Here, the uranium

Fig. 1: Pre-processed QUICKIRD image data acquired at July 24, 2002 over the NFRPC Esfahan

Fig. 2: Processed QUICKIRD image data acquired at July 9, 2003 over the NFRPC Esfahan
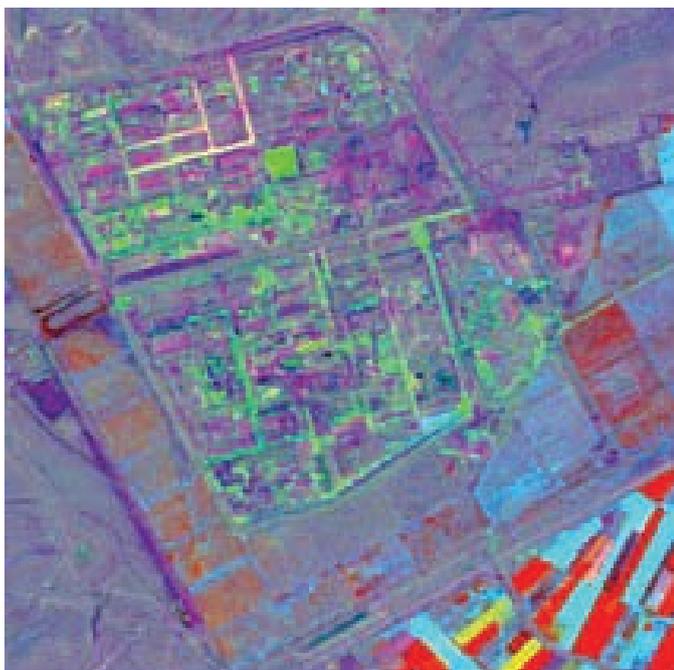
Fig. 3: Changes given by the MAD components 2 (red), 3 (green) and 4 (blue), without threshold
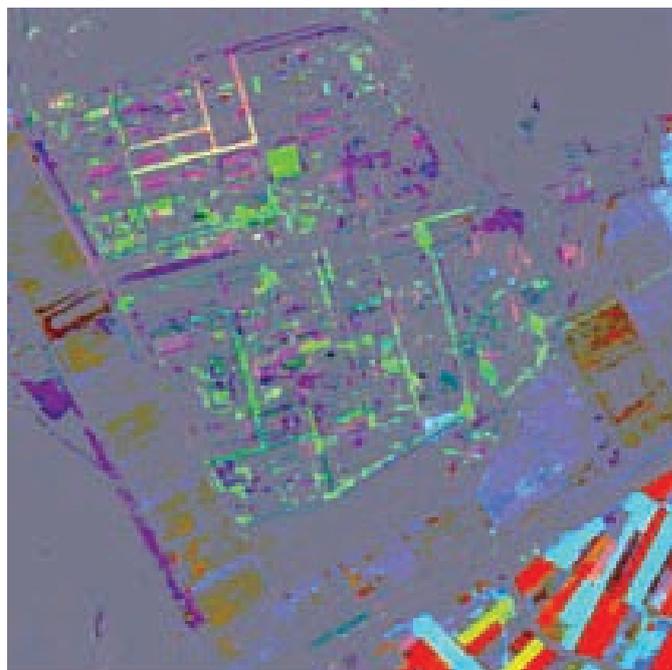
Fig. 4: Changes given by the MAD components 2 (red), 3 (green) and 4 (blue), with automatic threshold
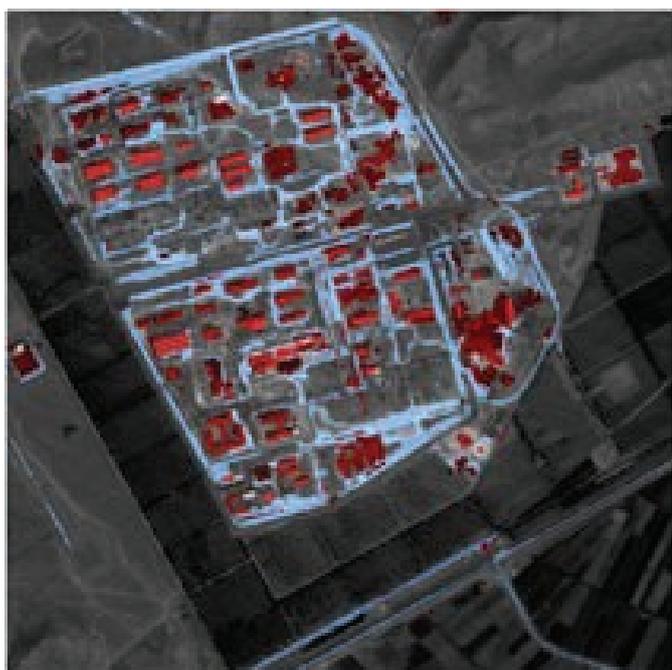
Fig. 5: Classification of buildings and streets for NFRPC Esfahan, July 2002
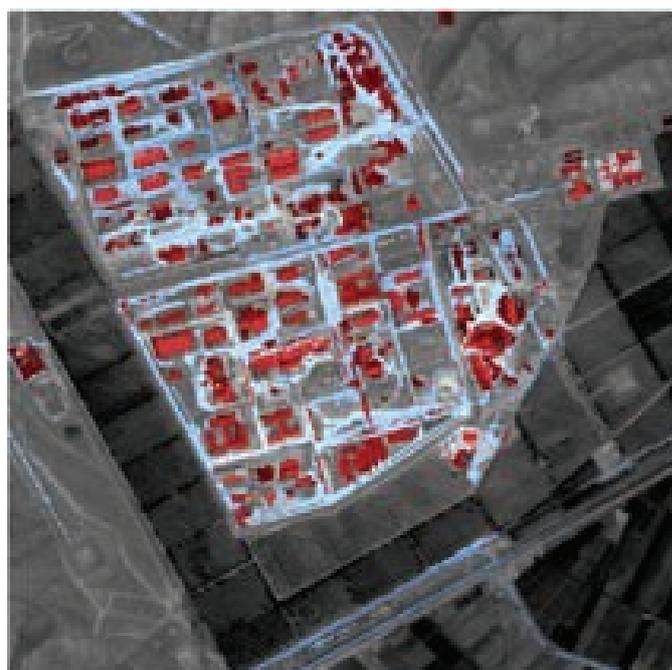
Fig. 6: Classification of buildings and streets for NFRPC Esfahan, July 2003

conversion facility and zirconium production plant will be monitored.

Both Definiens Professional 5.0 for segmentation and feature extracting and ENVI4.2/6.2 including the ENVI extensions for pre-processing, change detection and classification, provided by Morton J. Canty, Research Centre Juelich (http://www.fz-juelich.de/ ste/remote sensing, see also [25] for more information) were used. The QUICKIRD scenes acquired in July 2002 and in July 2003, displayed in

Figures 1 and 2, show a number of changes with different spatial and spectral dimensions. As noted in section 3, the four multispectral bands were first of all pan-sharpened by use of a wavelet transformation. Then, the image scene of 2003 was registered to the 2002 scene using feature based correlation. The co-registered were subsequently radiometrically normalised using no-change pixels.

The next step implies the change detection using the MAD technique. Figures 3 and 4 show the result

NFRPC, Esfahan, July 2002

NFRPC, Esfahan, July 2002

0	125	250	500	750	1,000

meters

🟥 New Streets   🟩 New Building Development

Fig. 7: Significant changes at Esfahan between July 2002 and July 2003, e.g. new buildings and streets

of the MAD components 2, 3 and 4 without and with threshold. The grey colour indicates no change areas, whereas the various colours represent different types of changes. Therefore, the changes within the facility, given mainly in green and magenta tones, vary from the changes in the surroundings, such as the red and cyan-coloured areas due to agricultural changes.

For analysing the type of changes, information on the land cover is needed and was generated by object-based classification. The object extraction was performed by the multi-resolution segmentation algorithm of the image analysis software Definiens Professional using with standardized parameters. Feature extraction and semantic modelling for the object classes *Building* and *Streets* were realized on the basis of the SEaTH method. The changes over time for these two object classes may indicate construction works between the two acquisition times. Figures 5 and 6 show the classification results of the object classes *Building* and *Streets* for 2002 and 2003.

Finally, the results from the pixel-based change detection and the object-based classification of 2003 were combined (Fig. 7). On the left, the 2003 image of is shown with indication of new buildings and streets. On the right, a detailed part of the zirconium production plant is shown for a comparison

of the 2002 and 2003 images with regard to new buildings and streets.

7. Conclusions

For nuclear safeguards purposes a methodology was developed, in order to facilitate the extraction of change information on nuclear activities using high-resolution multispectral satellite imagery. The presented procedure started with the automated pre-processing of high-resolution data, including pan-sharpening, image-to-image registration and radiometric normalisation. Changes between the two image acquisition dates were detected by means of the MAD technique and analysed in combination with an object-based classification.

The results of image classification and change detection were satisfying for the case study. Especially, the buildings and their changes were identified with a high accuracy. The combination of pixel-based change detection and object-based image classification has been proven to be a viable method to detect and identify significant changes in multi-temporal data. The automation of change detection and analysis procedures appears feasible to a certain extent, therewith giving rough and fast information on changes.

For a comprehensive change detection and interpretation system the signatures of nuclear

activities identifiable by satellite imagery have to be investigated and utilized for image processing. Moreover, also the automation of the procedures for orthorectification, object extraction, feature extraction and visualisation need to be improved or even brought forward.

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ESARDA Working groups activities in 2006
Summary report

Every year, the Working Groups are called for underlying their results and reporting them to the ESARDA Executive Committee. The Editorial Committee has compiled the most significant results achieved by various working groups and presents their results below.

In future, it is foreseen that the working groups highlight their most promising results in the spring issue of the ESARDA Bulletin.

1. The ESARDA Working Group on Containment and Surveillance
2. Achievements of the ESARDA NDA Working Group
3. Activities of the ESARDA Working Group on Integrated Safeguards
4. ESARDA Working Group Training and Knowledge Management
5. NMAC and Audit Focus group (NMACAF)
6. Editorial Committee activities

1. The ESARDA Working Group on Containment and Surveillance
Chairman's Report by Bernd Richter

In 2006, the working group had 21 members from R&D establishments, safeguards equipment manufacturers, safeguards inspectorates, plant operators, regulatory agencies, and ministries. They represented the ESARDA organisations: European Commission, Finnish and Swedish nuclear regulatory authorities, French Institute for Radiation Protection, Safety and Security, German Nuclear Fuel Cycle Association and Jülich Research Centre, and British Nuclear Group. Members from outside ESARDA represented the International Atomic Energy Agency, Argentine-Brazilian safeguards authority ABACC, Australian Safeguards and Non-proliferation Office ASNO, Canadian Nuclear Safety Commission CNSC, US Sandia National Laboratories, and Canberra Albuquerque company.

Recently, the working group addressed the following issues: IAEA Integrated Safeguards, implementation of the Additional Protocol, needs from Euratom safeguards approaches, design and simulation tools, performance & assurance of containment and surveillance (C/S) instrumentation, wireless in-plant data transmission, and proliferation resistance.

Recurrent activities are: information exchange and discussions on R & D within the working group, cooperation with other ESARDA working groups, compendium of C/S Instruments, support to the ESARDA working group on Training and Knowledge Management, and drafting of technical sheets for the ESARDA web site.

Achievements of the working group are publications in the ESARDA Bulletin, a presentation at the recent IAEA Symposium, and contributions to the ESARDA web site, such as a compendium on C/S instrumentation and technical sheets on: IAEA adhesive seal, electronic safeguards seals, review of surveillance data, fibre optic seal, and data transmission.

The working group's current major project is to develop a methodology for determining the performance and assurance of the C/S instrumentation. The first step will be to develop check list type templates for an application case concentrating on the performance aspect. The goal is to avoid subjective judgement. At later stages, other facility types and the assurance aspect will be addressed.

Another issue is wireless in-plant data transmission. The working group intends to provide a paper for publication in the ESARDA Bulletin. Furthermore, the working group addressed proliferation resistance and may be asked to provide consultancy support to JRC Ispra. Also a major issue is to provide input to the working group on Training and Knowledge Management for the Ispra Course on Safeguards. This will include a textbook contribution and a collection of viewgraphs. If possible, the working group intends to issue further technical sheets on: monitoring the movement of discharged fuel using

radiation monitoring techniques, ultrasonic seals, transponder seals, IAEA cap-and-wire seal, optical surveillance techniques, design information verification, mail box systems.

Future topics will be: C/S aspects of new safeguards approaches, guidelines on sealing and identification systems, containment verification methods and techniques, geological repositories, remote system control, data review, and IAEA next generation surveillance system.

2. Achievements of the ESARDA NDA Working Group

Chairman's Report by Paolo Peerani

In the field of general NDA instrumentation, the NDA WG has been active for many years in the assessment and the updating of a comprehensive list of performances values for NDA techniques currently used for the assay of nuclear materials. This resulted in the publication of the document "Performance Values for NDA techniques applied to safeguards" [1]. This document catalogues all the NDA techniques applied to Safeguards of nuclear materials, provides an extensive description of the principles, of the equipment and of the procedures and finally for each technique/application combination performs an accurate assessment of all the uncertainty components compiling tables of the real performances achievable with the NDA techniques. Another performance value document for NDA techniques applied to waste sentencing is in progress.

The use of unattended and remotely-operated instrumentation is becoming more and more used in nuclear safeguards in order to reduce the on-site inspection effort. Following a request of the IAEA and in collaboration with the Containment and Surveillance Working Group (ESARDA C/S-WG), a joint document on "Guidelines for developing Unattended Remote Monitoring and Measurement Systems" has been issued [2]. The scope of this document was to provide a list of technical specifications and requirements that unattended equipment must (or in some cases simply should) fulfil in order to be acceptable for field deployment.

In the field of gamma spectrometry several inter-comparisons have been organised in order to assess the capabilities of this technique. The last of these was the Pu-2000 exercise dedicated to the determination of the plutonium isotopic composition. The main purpose was to test the performances of recent X and γ spectrometry methods developed for determining Pu isotopic composition over a wide

range of abundances and to investigate possible sources of error. 20 plutonium-bearing reference samples have been prepared by the IRMM in Geel and measured by 8 laboratories using 18 different techniques (detector, acquisition chain and analysis software as MGA, MGA++ and FRAM). The results have been analysed and published [3]. Moreover compilation of uranium and plutonium spectra acquired during the Pu-2000 exercise and a previous one dedicated to uranium enrichment has been collected in the "ESARDA U/Pu Spectra Library" available on the web [4] for anyone who wants to use them to assess the performance of spectra analysis codes.

The benchmarking activity has recently found an important milestone in the organisation of the Workshop on "Gamma Evaluation Codes for Plutonium and Uranium Isotope Abundance Measurements by High-Resolution Gamma Spectrometry: Current Status and Future Challenges" held in Karlsruhe in November 2005. The workshop gathered 44 specialists from 12 countries including software developers, detector manufacturers, users from national laboratories and safeguards inspectorates (IAEA and Euratom). The current state-of-the-art of gamma spectrometry has been extensively evaluated and recommendations have been issued on harmonisation and version control, nuclear data standardisation, future requirement for unattended measurement and new materials from future fuel cycles, procedure optimisation.

A large interest is devoted to the application of Monte Carlo techniques to the numerical simulation of NDA instruments in general and neutron counters in particular. The use of MC modelling is becoming increasingly widespread as a tool for reducing the reliance upon experiment for calibration of neutron coincidence counting systems. 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:

- The first one dealt with the comparison of interpretational models used for the prediction of the real coincidence rates from a reference PWR fuel assembly measured with an active neutron collar when using the MCNP code [5].

- The second one was launched to analyse the influence of the main basic physical parameters (influence of fission spectrum, thermal treatment, cross section dataset, geometry model approximations) for Monte Carlo codes in common use on a simple case [6]: a point californium source placed at a fixed distance

from a slab detector with interposed layers of moderator (polyethylene) and absorber (cadmium).

- The most recent one intended to model a passive multiplicity counter. This last benchmark was split in two parts. A full simulation of neutron generation, transport and detection, coupled with the simulation of electronics had the purpose to compare coincidence counting simulation tools, such as MCNPX and MCNP-PTA. A second phase was aimed to compare only the pulse train analysis models, also studying dead-time effects, and all the participants analysed the same set of pulse trains. An AWCC in fast mode was chosen, considering a set of 13 sources: random sources, pure spontaneous (^{252}Cf and Pu metal) sources, Pu oxide samples and mixed random source/PuO_2 samples. The results of this exercise have been described in a final report [7].

- A follow-up of this benchmark has been recently launched. 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.

Under specific request of the IAEA, the NDA-WG is also 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, comprising both technical and non-technical considerations. Technical considerations will include the nuclear data used, the validity of the physics treatments and interpretational models, benchmarking the code under representative conditions, and the use of specific codes according to recognised procedures.

In the field of waste sentencing, the working group has sponsored the preparation of reference standard for measurements of nuclear material in waste drums. 16 waste drums have been produced having different size (100 and 200 litre drums) and different matrix (homogeneous/heterogeneous with plastic, metal or mixtures). These drums are provided with insertion tubes where different reference sources can be located. A set of 37 pins containing plutonium can be arranged in order to load the drums with masses ranging from 15 mg up to 10 g and simulate concentrated and distributed sources. Waste drums and sources are currently stored at SCK in Mol. The working group is currently organising an inter-comparison exercise of measurement techniques applied to the characterisation of plutonium in waste drums.

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[5] ESARDA Bulletin, # 31, (April 2002), pages 18-22.

[6] ESARDA Bulletin, # 33, (February 2006), pages 26-39.

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3. Activities of the ESARDA Working Group on Integrated Safeguards
Chairman's Report by Arnold Rezniczek

The ESARDA Working Group on Integrated Safeguards was created in 2000 with the objective to provide the Safeguards Community with expert advice on methodologies and approaches to integrate INFCIRC/193 and INFCIRC/540 measures and to present a forum for the exchange of information, views and experiences in that regard. Its members represent inspectorates, national authorities, operators and research centres active in the field of safeguards.

The Working Group very soon realized that a first milestone on the road to Integrated Safeguards is the successful and functional implementation of the Additional Protocol. Discussions and activities concentrated on actions necessary to reach this end thereby taking into account the specific situation in European States.

Among the topics discussed were issues of

- how to establish a functional site definition for different types of installations, ranging from small locations with very small amounts of nuclear material to complex installations with a complex history;

- how to deal with different and even conflicting requirements in the context of unannounced inspections;

- how to interpret and handle the requirements for R&D declarations considering the needs and interests of all parties involved; etc..

During its now seven years of lifetime, the group has proved to be very active and productive. The first constituting meeting started with six participants present. This number quickly increased and is still increasing with the accession of the new EU member states to now more than 20 members or observers from more than twelve European countries, with representatives from the inspectorates of EURATOM and the IAEA.

From our Point of view, the Working Group on Integrated Safeguards has very well met the expectations that called for the setting-up of the group. The group has proved to be very active and productive and makes the results of its work available to the safeguards community. A key output is the intense information exchange between the group members that also leads to the emergence of an harmonised view on key issues related to the implementation of the AP and the development of IS. The relationship developed with the IAEA allows a very open discussion and thus a good mutual understanding. It has always been our endeavour to find harmonized solutions that take into account the view of all parties involved in the implementation process, such as operators, national, regional, and international inspectorates.

With the Additional Protocol now in force in the European countries, a milestone of our work has been accomplished, but our task is not at all completed. The need for an intensive information exchange continues with the preparation for the practical implementation if IS in our countries. All this belongs to the necessary groundwork on which the development of the Integrated Safeguards approaches can be based and further developed or complemented in future. Examples of the topics the group may address in the next future are:

• A comparison of the pros and cons of treating the EU as single State compared with as individual States under integrated safeguards. One advantage could be that selecting randomly from a larger pool of facilities would result in fewer inspections in small States. A disadvantage was that addressing the borrowing scenario could prove more problematic;

• Practical solutions for the implementation of integrated safeguards at specific facility types from an operator's perspective. The fuel fabrication plant model currently under trial, or the IAEA model integrated safeguards approaches for each facility type, could be used as the starting point. Different methods of achieving the safeguards objectives could be compared and contrasted.

4. ESARDA Working Group Training and Knowledge Management
Chairwoman's Report by
Greet Janssens-Maenhout

Nuclear Safeguards and Non Proliferation Course by the ESARDA network

The knowledge retention problem in the nuclear field was acknowledged by the OECD in 2000. The European Commission recognized also this problem and has established in 2003 the European Nuclear higher Education Network (ENEN) association. The ENEN includes nowadays twenty-two universities and 13 other partners from nuclear industry, regulators and research centres from 18 different EU Member States. Every year, students are successfully accomplishing the academic curriculum and awarded a Master after Master degree in Nuclear Engineering. This curriculum, however, does not address safeguards and non-proliferation issues of the nuclear fuel cycle. In autumn 2003, the European Safeguards Research and Development Association (ESARDA) developed a strategy to tackle this problem.

Under the umbrella of ESARDA therefore, in 2004 a first training session on nuclear safeguards and non-proliferation was developed, which in the last 3 years has been further elaborated and was organised also this year in Ispra from March 5 to 9 2007. The very valuable contribution and "ownership" of the various ESARDA working groups to the training course modules makes it a unique European initiative, led by the ESARDA Training and Knowledge Management Working Group. The programme in the mean-time covers the why, what, who, where and how of the nuclear safeguards and non-proliferation topics, including information on the implementation (e.g. through inspections) and treaty monitoring and/or verification of party obligations. A full course syllabus, as reference material for the full academic recognition of this training is under development.

In the future this course will be repeated on a regular basis, and the aim is to have the course recognised as compulsory subject in the European Masters degree curriculum for nuclear engineering. Active as nuclear engineers, young professionals are confronted with nuclear law and should have received a correct understanding of nuclear technology, embedded in its legal framework. With this additional safeguards course, a newly trained

nuclear engineer receives the necessary basic knowledge of the relevant international agreements and regulations in the area of nuclear safeguards and non-proliferation (incl. the import/export of nuclear material and/or dual use goods…).

Given the international framework of nuclear law, the ESARDA course extended its access also to US and Russia, where similar initiatives are launched. The ESARDA Working Group Training and Knowledge Management collaborates with the International Atomic Energy Agency, US National Laboratories and Russian academic programmes. By enabling a Pan-European and even world-wide participation of students and lectures, the current curriculum for a European nuclear engineer is completed with an international view on today's non proliferation regime.

5. NMAC and Audit Focus group (NMACAF)
Chairman's Report by Brian Burrows

The ESARDA NMAC and Audit Focus group (NMACAF) fully discharged its Terms Of Reference within the one year target duration (March 2006 to March 2007). The outputs have been lodged on the restricted access area of the ESARDA website pending Executive and Steering group approval/action. The ESARDA Chairman subsequently instructed that the group outputs be made available in the open area of the website (email links will be sent to all ESARDA and interested parties) and clearly shown as having a status of "Pending Executive approval".

The WG exemplified the changes to the ESARDA Agreement aimed at enabling rapid, intense and short lived topical working groups. The 2007 annual Steering committee meeting concluded that the working group in its current formation and TOR has now terminated.

The products of the WG now need to receive wider consensus and an authoritative response from the Commission on the many suggestions and directions. There is also a requirement for ESARDA to set up a framework under which the WG guideline on "Good Practice NMAC" and the guideline on "Conduct of safeguards audit" can be maintained and enhanced by the ESARDA Community as living documents.

It is important to note that the NMACAF WG received limited input from the IAEA and from NNWS and it is necessary to foster more engagement with these stakeholders and trial audit in the NNWS environment to compliment the trials carried out in 2006 in the British and French bulk handling installations. Spain and Finland made formal offers to host trials and the WG chair asked that these include small and item facilities. Spain has also offered to pursue, via its support programme, the involvement of IAEA.

Given the considerable follow up work, ESARDA is considering how best to take this forward and whether the engagement of the IAEA in the audit deliberations should be under the auspices of the Integrated Safeguards Working Group. ESARDA members felt that the WG's success owed much to the targeted nature of the group and that a new group with fresh terms of reference should be formed to take the work through the follow up stages.

The WG reports will be taken again at the next ESARDA Executive meeting (autumn 2007) and prior to that the Commission has been asked to consider its response both on the reports and on setting up the NNWS trials. Member State experts who attended the Atomic Questions Group (AQG) meetings on the matter of the Commission EITS (Euratom safeguards implementation) document should also now receive some feedback from ESARDA. The Commission IETS document and the NMACAF output should ultimately converge and the Commission will review potential take up of the NMACAF documents in IETS.

The Steering Committee unanimously thanked Mr Burrows for his efficient and effective Chairmanship of the working group and for his well received paper and presentation at the 2007 ESARDA Symposium in Aix en Provence. The WG was highly commended on the detail and quality of the outputs produced in a relatively short time and considered as a valuable contribution by the Commission. Thanks were extended to the JRC for supporting the WG with meeting venues and by administering and hosting an intensive 3 day workshop. Thanks were also extended to Spain for hosting the joint NMACAF/IS meeting in Salamanca.

In the early days of the IAEA 93+2 strengthened safeguards initiative, there was much challenge about the legality of new safeguards measures and this ultimately led to the additional protocol. The advice from the NMACAF WG had been that proper legal council should comment on the legality of audit but other ESARDA members felt that this would open a very lengthy legal debate and could be avoided if the Commission would declare audit as a voluntary improvement measure. Audit has a place in the safeguards toolbox and its benefit will be best realised by continued collaborative endeavours.

Fig. 1: members of the NMACAF Group

6. Editorial Committee activities
Chairman and Secretary report by
B. Autrusson and L-V Bril

The ESARDA Bulletin

The decision to issue the Bulletin twice a year was taken in 2005. The Editorial Committee has implemented the first year of regular release with the issues 33 (February) and 35 (December), with one special issue 34 on NDA (September).

For the first time a section of peer reviewed papers has been implemented and will be carried on.

Future Bulletins will be regularly issued in June and December of each year. Special issues addressing topical questions may also be released outside this time-schedule.

The preparation of the Bulletin 36 (June 2007) was started in 2006.

The preparation of **the 2007 symposium** was begun very early. The call for paper was released in February 2006 and resulted in an exceptionally high number of abstracts submitted: 80 abstracts were submitted by the deadline (24 November 2006), 163 by the end of the year and 175 in total. The elaboration of the programme was made at the December meeting.

The preliminary programme was made available on the website at the end of February 2007.

The website, which is an important communication medium was constantly updated with material provided. The Bulletins were posted and are available from the corresponding section. To be noted: the Working Groups are now using the restricted area of the website and post regularly the material discussed during their meetings, for the benefit of their members and the members of other Working Groups.

Wireless Communications for Monitoring Nuclear Material Processes PART I: Context and Technologies

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Abstract

Recent advances in radio frequency communication technologies offer the motivation to consider the use of wireless communication in nuclear safeguards applications.

From the Nuclear Safeguards Inspectorates' (NSI) point of view, wireless data transmission – which would be supplemental to wired communication – is attractive for the ease of installation and the ability to respond to the changing requirements as the inspection approach evolves, resulting in a reduction of costs. However, for wireless technologies to be considered as a viable complement to cables, a number of concerns have to be addressed.

First, nuclear operators need to be guaranteed that RF transmission will not interfere with the facilities safety and physical security systems. On their side, the NSI must be satisfied that Containment and Surveillance equipment and data transmission processes will not be affected by the other existing RF equipment.

Second, it is desirable, both for the NSI and the operators, that the data being transmitted is not available for analysis by a third party. In addition, the NSI require data to be authenticated as close to the point of acquisition as possible.

This paper was prepared as an account of work performed and approved by the ESARDA Working Group on Containment and Surveillance. It is the first of a suite dedicated to bridging RF technologies with safeguards monitoring applications. The paper focuses on technological issues: it introduces basic concepts underlying wireless communication, including methods for transmission, issues on power consumption, frequency, range, and considerations on interference and noise resilience. It overviews state-of-the-art wireless technologies and presents a projection on wireless capabilities that are likely to be reached in the near future.

1. Introduction

Over the past several years, evolving radio frequency (RF) communication technologies have significantly expanded the possibilities for utilizing wireless communications in applications where once wired communication was the only alternative. These advances provide the incentive to consider the utilization of wireless communication technologies in nuclear process and operation monitoring systems.

It is envisioned that RF communications applied to safeguards monitoring situations would be supplemental to hardwire communications and not a replacement. Wired communications still maintain advantages in certain areas that cannot be addressed by simply installing a wireless RF link. Fundamentally stated, wires do not radiate energy to the extent that RF communications do. This is a concern for some facility operators who worry about sensitive information being disclosed to eavesdroppers. Also, wires are virtually interference free, while RF may be vulnerable to interference and even being blocked, shielded, jammed and monitored. It is also true, however, all of these RF issues can be addressed and mitigated to a great extent through advances both in the technology and protocols.

Another important consideration for hardwire based communication is that if wires are used for transmitting sensitive data, they should be examined frequently or installed in a protective shield to add resistance to in inadvertent damage and intentional splicing: this effort represents a high level of expense. A more effective approach is to authenticate the data before transmission, which is the same way that sensitive data is protected in wireless applications.

As a summary, low installation cost, minimal impact to the existing infrastructure and system versatility

are some of the prospected advantages of RF over wired communications.

This paper was prepared as an account of work performed and approved by the ESARDA Working Group on Containment and Surveillance. It is the first of a suite dedicated to bridging RF technologies with safeguards monitoring applications. The paper focuses on the technological issues and describes the state-of-the-art in wireless communications under the context of safeguards applications. It should become clear that there is not a technical solution that fits all safeguards situations. Indeed, as in many other areas, any solution is the result of a study and trade-off involving many factors, some technical, others non-technical. Another aspect to take into account is the continuous development of wireless technologies with standards being issued at a very fast rate. This technological 'volatility' should also be considered when selecting a wireless communication solution.

The paper is organized as follows. **Section 2** provides specific arguments, from a Nuclear Safeguards Inspectorates' (NSI) perspective, for considering the use of wireless communications as a complement to fixed cables installations. This section also pin-points specific challenges to be addressed for wireless technologies to be deployable in facilities satisfying requirements arising from the operators and the NSI. **Section 3** introduces basic concepts underlying wireless communication [1], including methods for transmission, issues on power consumption, frequency, range, and considerations on interference and noise resilience. **Section 4** overviews state-of-the-art wireless technologies and makes a projection on capabilities that are likely to be reached in the near future. **Section 5** summarizes and highlights the main points presented in the paper.

2. Installed Safeguards systems

Nuclear Safeguards Inspectorates. NSI have as a basic objective the requirement to 'satisfy itself that nuclear materials are not diverted from their intended uses'. The role of the nuclear operator as the first actor responsible for material control within his installation is assessed by the safeguards authorities through independent verification of nuclear material flows and inventories.

Containment and surveillance. The safeguards approach calls for the application of containment and surveillance under specific circumstances, i.e., in order to freeze certain strata of nuclear material or to enhance observation of plant activities, when

judged necessary. In addition, the NSI needs to perform independent nuclear measurements to confirm the operator's declaration.

Fixed and mobile instrumentation, data collection, remote data transmission. The NSI may use their own instrumentation. Ideally, a feasibility study combined with a detailed cost-benefit analysis should be carried out in order to decide whether to use portable/mobile or installed equipment. Fixed instrumentation will be installed at strategic points of the process flows. Whenever possible and appropriate, installed instrumentation will run in unattended mode. In addition to the on-site data collection activities, there is a requirement for effective and reliable remote data transmission back to a central location which could be the on-site safeguards inspector's office or the NSI headquarters.

Issue related to fixed instrumentation. In general the installation of fixed instrumentation is undertaken during the construction phase of a nuclear facility. Cables for the exclusive use of the NSI are run to the points identified by the safeguards strategy at the facility. This requires close co-operation between operators and inspectors to ensure that equipment is located at the optimum position. There is a degree of risk associated with this activity as decisions must be taken during the design phase on layout drawings before any physical construction has begun. Any changes in the design which affect the utilisation of safeguards equipment must be recognised and communicated by the operator to the inspector. The physical installation of safeguards equipment is made during the non active commissioning phase. It is only at this time that the reality of data collection can be evaluated against the original safeguards approach requirements. Any changes required at this stage would have a direct impact on the commissioning schedule as the inspectorates would not allow active commissioning to take place until an appropriate safeguards system is operational.

It is also true that over the lifetime of a nuclear facility there are often changes in the way the facility operates. Additionally, there may be modifications to the existing equipment used in the operation of the facility or other actions such as increased biological shielding. These changes may lead to modifications in the safeguards approach. Finally, due to the long operating periods of nuclear facilities i.e., many tens of years, the inspectors equipment will become obsolete. The replacement equipment will be required to operate using the existing cabling and as such the choice of technology may be limited by cable compatibility.

Once it is determined that the safeguards approach requires change, the challenge of installing new equipment to meet the new conditions arises. At this stage the plant has almost certainly been operational for a number of years. Nuclear facilities impose specific requirements to the installation of equipment due the effects of radiation and radioactive contamination. These issues combined with the physical construction (e.g. very thick walls used as biological shielding) impose yet further severe challenges which need to be overcome. Experience has shown that the installation of new cabling is expensive and takes a considerable time before a final solution is installed and operational.

Appeal of wireless communication to safeguards. Given the limitations generated by the installation of fixed equipment, it is quickly recognised that the use of wireless data transmission would represent a huge advantage both in terms of installation and ability to respond to the changing requirements of inspectors as the inspection approach evolves. However, for wireless technologies to be considered as a viable complement to cables, a number of safeguards and operators requirements have to be satisfied first.

Challenges for deployment of wireless links in facilities. First, NSI require data to be authenticated as close to the point of collection as possible. This means that it would not be feasible for an adversary to deceive the inspector that the information s/he is evaluating does not come from another source. Second, it is desirable, both for NSI and the operators, that the data being evaluated is not available for analysis by a third party. Finally, the nuclear operators need to impose limitations on the transmission standards which can be used on nuclear facilities due to the possibility of interference with their safety and physical security systems. Likewise, NSI need to be guaranteed that the C/S equipment and the data transmission process is not affected by the operators' RF equipment. The physical construction, e.g., large steel surfaces or vessels and thick concrete walls also complicate the choice.

Given the list of challenges above, we need to consider if the technology currently available or soon to come can meet these challenges.

3. Basic wireless communication concepts

3.1. Transmission methods

There are two fundamental RF transmission techniques – narrowband and spread-spectrum [2].

Narrow-band RF. Narrowband RF concentrates all of the transmitted energy into a relatively narrow frequency width. Because of this characteristic, narrow band systems typically have greater range for a given power output. This technique allows for the use of less expensive and less sensitive RF devices, but a significant drawback to narrowband transmission is its susceptibility to jamming (whether it is an intentional or environmental cause). Additionally, with narrowband RF, the probabilities of detection (PD) and interception (PI), and therefore the possibility of eavesdropping by unauthorized parties outside the facility, is relatively high and does not require sophisticated equipment. Narrowband transmissions can be either a variety of amplitude modulation (AM) or frequency modulation (FM).

Spread-spectrum RF. Spread-spectrum RF transmission techniques utilize a method of distributing the transmitted power over a relatively broad spectrum of frequencies or time. This is done for a variety of reasons. If the transmitted power is at the same level of that of the narrowband technique, then it can be seen that the power at a given frequency will be substantially lower than the narrowband transmission. Based upon this capability, the transmitted signal becomes more secure, due to the increased difficulty to find the signal in the noise, and the transmissions become much more resistant to jamming, interference and RF nulls (dead zones). However, the point to point/node to node relative transmission distance decreases.

Direct sequence and frequency hopping in spread-spectrum RF. Typical features of spread-spectrum include direct sequence (DS) and frequency hopping (FH) for distributing the RF transmission over the spectrum. These techniques utilize frequency-hopping patterns to break up the transmission in a pre-determined sequence which is then recovered by the receiving device following the same pattern. These capabilities provide added security because an adversary will require more sophisticated equipment for finding the signal and, in the case of FH, it will need to know the hopping sequence.

Extreme protocols further enhance security. Today, many commercially available data communication systems utilize spread-spectrum transmission for wireless communications because of the characteristics described above. The security provided by these systems is continuously improving due to the requirements of more demanding applications. Safeguards applications are a somewhat unique application regime because the

security requirements are significantly greater than that perceived as required in the commercial and industrial scope. The consequences of interpreting false data in the safeguards regime as true or authentic are very substantial. In certain instances commercially available RF communication techniques may not meet the stringent security requirements imposed by safeguards and therefore extreme protocols are needed. These protocols can be added at a system level (e.g., virtual private network) [3] or embedded at the lowest level of data acquisition such as authentication in a secure, tamper indicating enclosure (TIE) of a low power sensor.
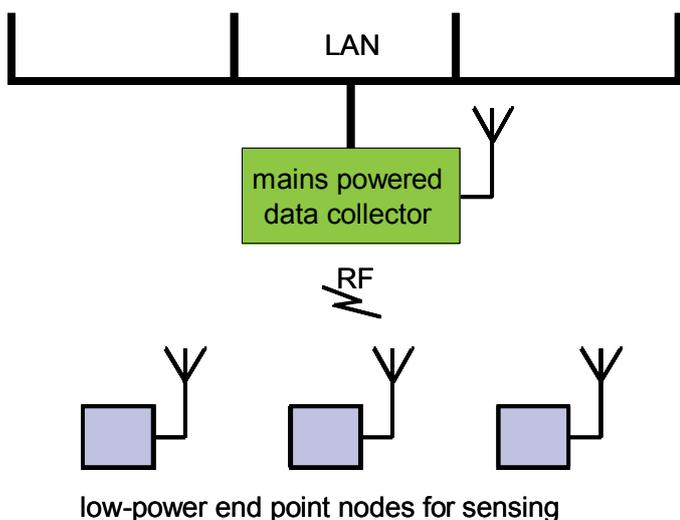

Figure 1: Ultra low-power sensor configuration.

3.2. Power consumption

There are many wireless communication configurations available for consideration in safeguards. It is not the intent of this paper to discuss these in detail. However, an important subset will be mentioned here. These methods can be introduced based upon the amount of relative power required to perform its intended function.

Typically stated: 'the more power consumed, the greater the data handling capability of a given method'.

Ultra low power devices. At the lower end of this spectrum are ultra low power devices such as sensor nodes and active seals. These devices conserve power by spending the majority of their life sleeping (up to 95% of their deployed life), periodically waking up to perform routine functions such as: listening and responding as required, retrieve sensor data and report. These types of devices usually provide periodic state-of-health (SOH) information to verify that the device is alive and communicating. The simplest implementation of this type of system is end point nodes (battery-powered sensors) communicating point-to-point with a continuously powered data collector or gateway (Figure 1). At this level, the nodes are able to communicate bi-directionally but only in half-duplex (one direction at-a-time) with the data collector. The data collector is then connected to a higher level communication system such as wired or wireless LAN (e.g., 802.11 [4]). Because sophisticated communication and security protocols can be embedded into the end point nodes, this configuration can represent the greatest level of security and establishes the highest confidence data collection in a safeguards monitoring concept.

Medium power consumption: Motes and Zigbee. The next level of relative power consumption is represented by RF systems that utilize concepts such as the IEEE 802.15.4 or Zigbee [5], a communication standard. Examples of implementation of this standard are the Motes by Crossbow Technology, Inc. (Figure 2, left) [6]. The system architecture includes both battery- and mains-powered devices (Figure 2, right). The battery-powered devices become the end points of the configuration similar to the ones described in the previous paragraph. To extend range and
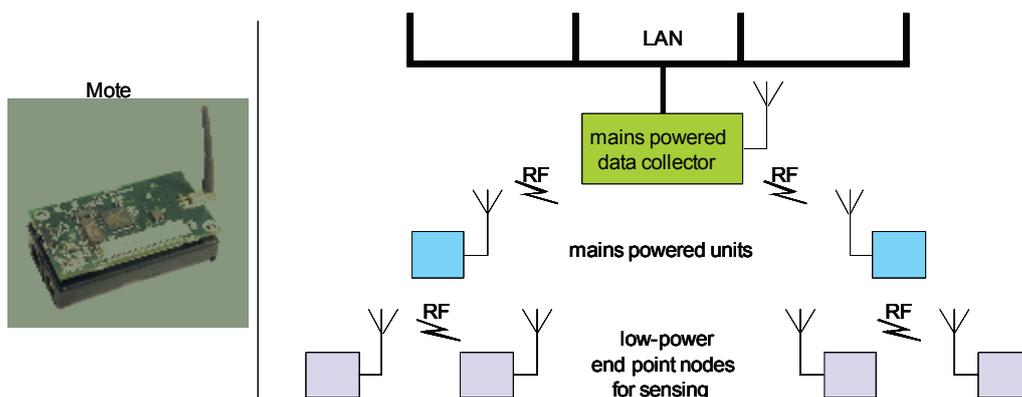

Figure 2: A Mote by Crossbow Technology (left) and the extended range configuration of Zigbee (right).
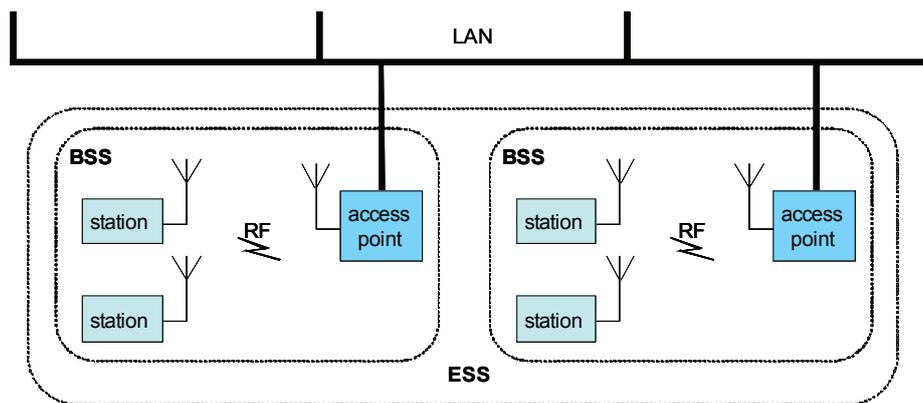
Figure 3: Extended Service Set with access point to LAN.

support mesh networking, mains powered units are added to the configuration to support message routing and network management. Finally, a data collector is provided to transfer RF communications to the system level and distribution. Typically, this architecture is designed to support environmental monitoring, building automation and asset management. It allows for the easy and fast creation of a 'Wireless Sensor Network' [7] that can arrange itself in a self-organized way.

High level power consumption: Wireless Local Areas Network (WLAN). 802.11 or WLAN [4] represents the highest level of power consumption discussed in this paper and provides the reader with an understanding of the scope of capabilities of RF based communication systems. WLAN is intended for seamless and relativity high bandwidth data communication. The capabilities of WLAN can virtually replace wired communication for localized areas. Because this is an RF system, there is significant concern regarding the security of transmissions. Fundamental concerns are related to eavesdropping on RF transmissions and access point substitution. To address these issues Advanced Encryption Standard (AES) and Wi-Fi Protected Access (WPA) protocols have been implemented in the latest standard [8]. The evolution of 802.11 has been driven primarily by security weaknesses that have been discovered mandating improvement in communication protocols. These issues must be considered when WLAN is implemented for safeguards use. Notwithstanding, additional security measures should be applied to sensitive information prior to its introduction into any wireless LAN system. The otherwise seamless operation and high bandwidth of WLAN make this system of communication quite appealing for versatile, medium-long ranges LAN applications. Figure 3 shows a 802.11 configuration with two independent

Basic Service Sets (BSS) connected through access points to a LAN.

3.3. Frequency

Unlicensed bands. The two most utilized unlicensed RF bands are 900 MHz and 2.4 GHz. Both the 900-MHz and 2.4-GHz bands reside in the Industrial Scientific Medical (ISM) bands [9]. The actual unlicensed frequency bands in the ISM are of 902 to 928 MHz, 2.4 to 2.483 GHz, and 5.725 to 5.875 GHz. Today almost all of the transceiver and system-on-a-chip (SOC) products targeting wireless sensor network applications use the 900 to 928 MHz and 2.4- to 2.483-GHz bands. The 900 MHz band touts long broadcast range because of its relatively longer wavelength and its correspondingly longer battery life. However, a lower frequency requires the use of a larger antenna than a 2.4-GHz system.

Lack of standardization. An additional problem encountered is the lack of standardization in the 900 MHz range. For example, in Europe, the 900- to 928 MHz band is unavailable because it is part of the Global System for Mobile (GSM) network for cell-phone communication. This requires the use of either the 433 MHz band or jumping up to the 2.4 GHz band. Table 1 [10] illustrates typical international unlicensed frequency bands that are currently being utilized.

3.4. Range

RF propagation and the associated range [1, 11] are a complicated science and one that is far beyond the scope of this paper. There are, however, a few good concepts regarding this subject that can provide the reader with a fundamental understanding of the circumstances that affect the range of RF transmissions.

For safeguards applications utilizing the unlicensed frequency bands, it can be generally stated that the

RF frequency (MHz)	Transmit power	Typical range (meters)	Comment/Usage	Country
13.56	High	10	Very narrow bandwidth, ISM band, industrial plasma welding, "contactless" smart cards	World
303.825	Low	2	Very low power, car door alarm, control	Japan, Korea, USA
303.825	Medium	20	Car door alarm, control	USA, Australia
315.0	Medium	20	Car alarms, garage doors	USA, Canada, Italy
433.92	Medium	20	SRD Car alarms, garage doors, telemetry	Europe
868.0-870.0	High	10-30	ISM band, data networks, telemetry	Europe
916.5	High	10-30	ISM band, high power, telemetry, data networks	USA
2400.0	High	10-100	ISM band, microwave oven and RF lighting, data networks, telemetry	World (Asia and Europe restrict bandwidth)

Table 1: Unlicensed international Electromagnetic Spectrum (EMS) regulations.

higher the frequency the shorter the range for a given transmit power. Direct or line-of-sight propagation (i.e., antennas visible to each other) is the ideal circumstance for obtaining the greatest effective range of RF communications. Table 2 shows some typical examples [11].

Environment	Range (meters)
Dense cubical office space	13
Open retail space	31
Large open area	62
Free space (outside)	175

Table 2: Typical RF signal propagation of a 1 miliWatt 916 MHz transmitter in various environments.

3.5. Interference and noise resilience

Today a RF based monitoring system supported by wired communications, has in its toolkit processing capabilities and protocol implementations that can address and substantially mitigate the known common problems and vulnerabilities.

Transmission error: detection and recovery. RF transceiver firmware is now capable of performing sophisticated error detection and recovery without processor interaction [12]. Typical processes found in state-of-the-art RF transceivers include forward error correction (FEC), data whitening, or the process of balancing modulation, as well as data interleaving. The fundamental purpose of these data processes is to increase the robustness of RF communication. Another important gain in current and future RF system designs can be seen in receiver sensitivities, which are increasing substantially. It is not uncommon for an FM narrowband receiver to have a sensitivity of greater than -110dBm at reasonable data rates. This fact extends ranges and allows for operation in noisier environments.

RF interference. Interference [13] is very much dependent on the geometry and on the devices that are found in the environment. It is a major a concern for both the operators and the NSI. First, interference is to be avoided as it could hamper safety and physical security systems existing in facilities. Second, NSI C/S equipment and data transmission are not to be affected by interference generated by other RF equipment.

Prior to any RF system implementation, the environment where it will be utilized must be understood and controlled after installation. It is difficult, at best, to design an 'RF friendly' building and most existing facilities did not consider RF requirements when they were constructed. An RF survey of the application site is a typical process employed to identify possible existing sources of electromagnetic radiation that could cause interference with desired RF transmission. Additionally, unexpected changes to the RF environment can be introduced by simply moving existing equipment or installing new equipment which can cause undesirable RF side effects in the form of interference, RF nulls and multipath. Issues such as multipath can be addressed through the RF system design, proper antenna system design, and building or environmental alteration. It cannot be understated the importance of thoroughly assessing the environment where an RF system is intended to be deployed. Periodic RF re-assessments are also recommended and should be performed by experts in the RF field and ones familiar with local and regional RF regulations and standards.

Although preventing interference implies an additional cost, it is a quite well understood problem: procedures and best practices exist to deal with it as it is a shared issue to several industrial sectors using RF devices.

Management of RF traffic. Another very important aspect of an RF system is how RF traffic is managed [14]. As an example, WLAN supports an access control or monitoring protocol where devices detect and acknowledge ongoing RF traffic. This is typically termed 'listen before talk' or polite protocol. It can be implemented through a coordinated protocol such as carrier detect/sense multiple access: this implies that the device wishing to broadcast must first sense if the channel is currently occupied. If this is true, the device will wait for some period of time (usually random set back) before attempting to transmit again to avoid collisions. This brings into focus the importance of managing the use of unlicensed RF devices in the area where coordinated RF communication is ongoing. For example, if an 'impolitÈ device begins operating in the same frequency band, collisions will occur resulting in errors. A wireless telephone is an example of an impolite transmitter. The overall effect of collisions can range from reduced effective data bandwidth to a denial of service. RF communication systems can easily recover from the majority of these interruptive scenarios. If a message is not received intact, the corrupt packet, or in some cases the entire message, is simply retransmitted when the interference is discontinued. This is why the effective data bandwidth is reduced.

4. Overview of current and emerging wireless technologies

The characteristics of today's major wireless technologies are summarized in Table 3.

Bluetooth. Bluetooth is suitable for Wireless Personal Area Network (WPAN) applications for it offers ranges of between 10 to 100 meters depending on the class of the transmitter. It supports speeds of around 1 Mbps. It is especially used over short distances to link wireless peripherals to a central computer (PDA, keyboard, mouse, etc.). Bluetooth technology uses the ISM (Industrial, Scientific & Medical) frequency band reserved for these applications. It employs frequency hopping to transfer information. Bluetooth technology has suffered plenty of interoperability. It does however consume less power than WLAN and is therefore preferred for applications that require only limited speed.

ZigBee. ZigBee has been developed to meet the market needs of 'Wireless Sensor Networks' [7]. It is intended for sensors that need some bandwidth (but not much) over short periods of time. ZigBee consumes low power, while allowing for ranges of around 10 metres without the need for a signal repeater. It integrates encryption functions into the lower layers of its implementation (specifically, AES encryption).

Despite of these positive features, the ZigBee standard is not yet usable industrially. Tests performed on three different development kits have shown that vendors have not yet developed ZigBee chips that are full compatible with 1.0 level specification for this standard [15]. Interoperability between all vendors will only truly become effective once all comply with the standard (802.15.4).

This technology is therefore penalised at present by its lack of maturity. The development and success of the ZigBee technology are dependent on the willingness of vendors to see their equipment

Technology	Application	Transmission method	Comment
Bluetooth	Connect and exchange information between devices such as mobile phones, laptops, PCs, printers, digital cameras, wireless mouse and video game consoles. Battery powered devices.	2.45 GHz PAN low power, short distance and low data bandwidth.	Security issues throughout its history, but they have been addressed and adapted. Very versatile for short range devices connections
Zigbee	RF applications that require a low data rate, long battery life, and moderately secure networking.	ISM bands 868 MHz in Europe, 915 MHz in the USA and 2.4 GHz in most jurisdictions worldwide. Self organizing, ad hoc network with more than 100 nodes.	
WLAN 802.11	High bandwidth with network management	Most widely use in the 2.4 GHz band. Spread spectrum	

Table 3: Today's major wireless technologies.

Protocol	Release date	Op. frequency	Data rate (typical)	Data rate (max)	Range (indoor)	Range (outdoor)
Legacy	1997	2.4-2.5 GHz	1 Mb/s	2 Mb/s	?	?
802.11a	1999	5.15-5.35/5.47-5.725/5.725-5.875 GHz	25 Mb/s	54 Mb/s	~25 meters	~75 meters
802.11b	1999	2.4-2.5 GHz	5.5 Mb/s	11 Mb/s	~35 meters	~100 meters
802.11g	2003	2.4-2.5 GHz	25 Mb/s	54 Mb/s	~25 meters	~75 meters
802.11n	2007 (draft)	2.4 GHz or 5 GHz bands	200 Mb/s	540 Mb/s	~50 meters	~126 meters

Table 4: Summary of 802.11 developments.

Technology	Application	Transmission method	Comment
Ultra-wideband (UWB)	High data rate short range communications. Possible application in PAN (personal area networks. Short range radar and positioning tracking.	Information spread over a very wide (>500Mhz or 25% of the center frequency) bandwidth in the 3.1–10.6 GHz band. Pulse position or time modulation.	Virtually immune to typical multi-path problems. Short range limits possible applications.
Secure Sensor Platform (SSP) System	Low maintenance devices used where very high confidence data collection is required. Interface supports a variety of sensors and seal. Public key based authentication.	FM narrow-band, ultra-low power utilizing infrequent burst communications.	Commercially available Dec. 2007. Can last several years on a single battery.
RuBee	Asset tracking utilizing passive RFID and low bandwidth communication. Low speed inexpensive technology.	Long Wave (LW) magnetic signals to transfer information below 450 kHz and optimally at 132 kHz.	Final stages of IEEE development.

Table 5: Prospective wireless technologies.

progress towards a full implementation of the standard, one which will ensure that the standard's strong points are implemented (topologies, security) as well as full interoperability between all equipment.

WLAN. 802.11, WLAN is probably the most widely utilized unlicensed RF communication method and can likely be the backbone of any wireless implementation for safeguards monitoring. Simply stated, WLAN can efficiently and seamlessly move large amounts of information. However, WLAN is easily monitored because it utilizes standard low-cost hardware and there is an abundance of traffic for an adversary to study. As this standard has evolved (Table 4, [16]), security protocols have improved significantly making it increasingly more difficult to listen intelligibly. Additionally, sophisticated security measures can be embedded at device level to further address this issue. This standard began in 1997 with '802.11 legacy'. The current version, 802.11i, implements Advanced Encryption Standard (AES) and Wi-Fi Protected Access (WPA). 802.11n is expected to be realized in 2007. This gives the reader an impression of how rapidly the technologies are evolving and adapting to more security rigorous and robust requirements.

Prospective wireless technologies. Ideally the future of RF data communications will bring forth technologies that will be more secure, provide much greater bandwidth and be entirely battery powered. RF transceivers that are available today demonstrate a trend that will continue regarding the development of more highly integrated RF systems-on-a-chip (SOC). It is reasonable to expect to design an RF device that utilizes a transceiver integrated circuit with a integral microprocessor which providing functions such as encryption, error detection/recovery and collision avoidance. In the past these processes were burdened by the main processor. Moving this functionality off the main processor eliminates the need for developers to incorporate them into their software and provides for consistent implementation, an absolutely requirements for today's and tomorrow's communications. This is just one example of the interesting advances we are seeing RF technology. Table 5 lists near-term projections for what the future will offer.

Finally, Figure 5 shows the vision and the technology roadmap for wireless communication as developed in the context of industrial control and automation. This Figure is presented by the EU-funded project RUNES (Reconfigurable Ubiquitous Networked Embedded Systems [17]). It is to be noted that many of the issues at the heart of the vision put forward by this industry are positively correlated with safeguards requirements on wireless: namely, the

Technology	Application	Transmission method	Comment
Ultra-wideband (UWB)	High data rate short range communications. Possible application in PAN (personal area networks. Short range radar and positioning tracking.	Information spread over a very wide (>500Mhz or 25% of the center frequency) bandwidth in the 3.1–10.6 GHz band. Pulse position or time modulation.	Virtually immune to typical multi-path problems. Short range limits possible applications.
Secure Sensor Platform (SSP) System	Low maintenance devices used where very high confidence data collection is required. Interface supports a variety of sensors and seal. Public key based authentication.	FM narrow-band, ultra-low power utilizing infrequent burst communications.	Commercially available Dec. 2007. Can last several years on a single battery.
RuBee	Asset tracking utilizing passive RFID and low bandwidth communication. Low speed inexpensive technology.	Long Wave (LW) magnetic signals to transfer information below 450 kHz and optimally at 132 kHz.	Final stages of IEEE development.

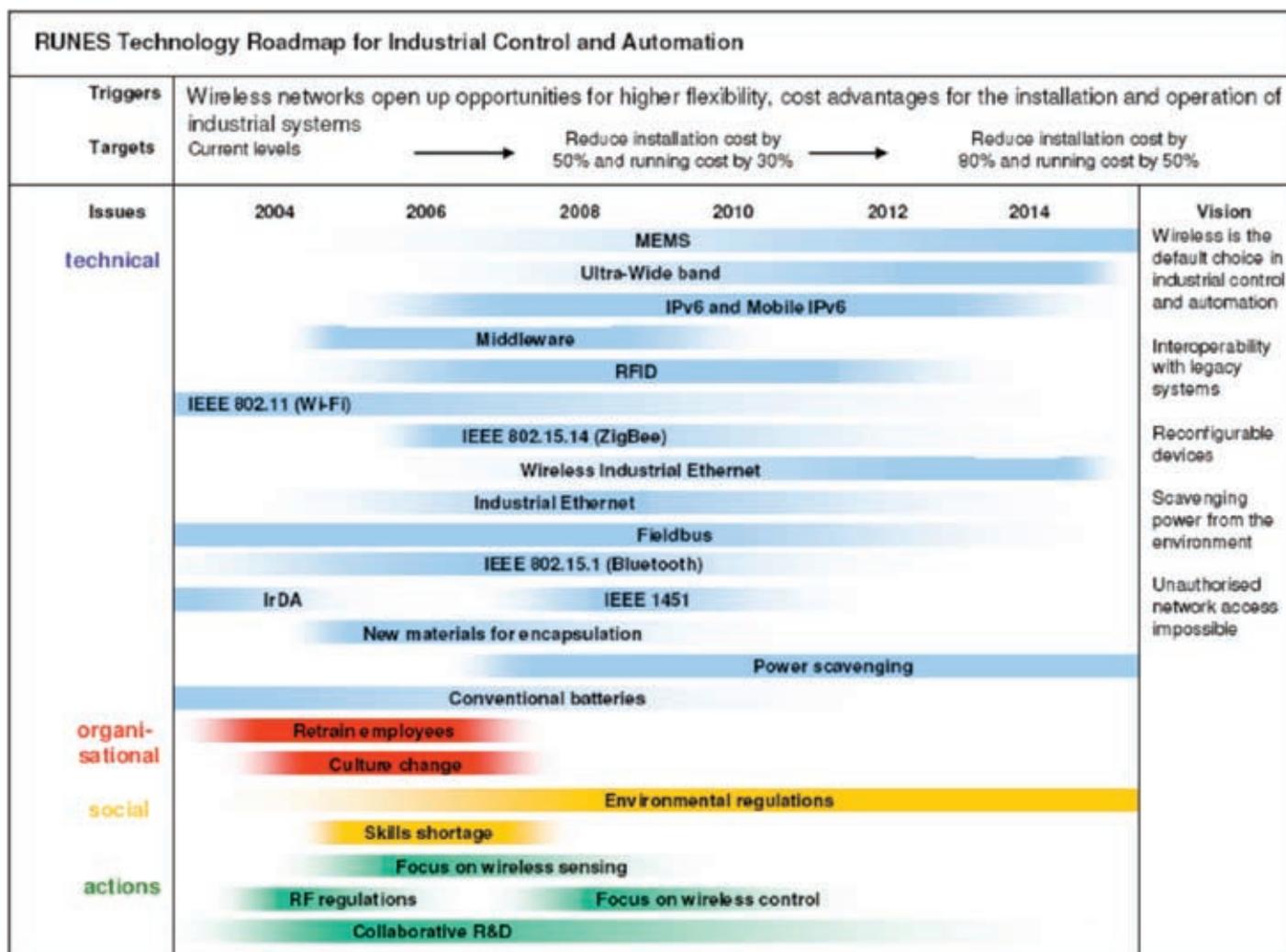**Table 5: Prospective wireless technologies.**

Figure 4: The RUNES technology roadmap for industrial control and automation.

needs for 'interoperability with legacy systems', 'reconfigurable devices' and 'unauthorised network access impossiblÈ. In the same way, the aims for achieving 'higher-flexibility' and 'cost-advantages' are shared by safeguards applications. Industrial control and automation has a very wide industrial base and is a driving force for new developments on wireless: it is reasonable to expect that a substantial part of this vision will be realized. Safeguards will then be in a position to profit from the resulting technologies and concepts.

5. Summary and outlook

Recent and expected advances in radio frequency communication technologies offer the motivation to consider the use of wireless communication in nuclear safeguards applications.

From the Nuclear Safeguards Inspectorates' point of view, wireless data transmission – which would be supplemental to wired communication – is attractive for the ease of installation and the ability to respond to the changing requirements as the inspection approach evolves.

However, for wireless technologies to be considered as a viable complement to cables, a number of concerns have to be addressed.

First, nuclear operators may need to impose limitations on the transmission standards to be used in facilities to avoid interference with their safety and physical security systems. On their side, NSI need to be guaranteed that C/S equipment and data transmission processes will not be affected by the other existing RF equipment. As such, prior to any RF system implementation, the environment where it will be utilized must be understood (e.g., by an RF survey), controlled after installation, and periodically re-assessed. Although preventing interference implies an additional cost to installation and maintenance, it is fair to say that interference is a quite well understood problem: procedures and best practices exist to deal with it as it is a shared issue to several industrial sectors using RF devices.

Second, it is desirable, both for the NSI and the operators, that the data being transmitted is not available for analysis by a third party. In addition, the NSI require data to be authenticated as close to the point of acquisition as possible.

As a general trend, it is noted that the data security provided by RF communication systems is continuously improving due to the requirements of more demanding applications in various industrial sectors. In certain cases, stringent data security

requirements imposed by safeguards may be addressed by extreme protocols embedded either at system level or at the lowest level of data acquisition.

WLAN, probably the most widely utilized unlicensed RF communication method, is one instance of a standard whose evolution was driven mainly by the need for more security. As an example, Advanced Encryption Standard (AES) and Wi-Fi Protected Access (WPA) protocols have been implemented in the latest version of this standard. The trend towards 'more robustness and security' in wireless communication is also testified by the appearance on the market of RF transceivers as highly integrated systems-on-a-chip, providing functions such as encryption, error detection/recovery and collision avoidance.

Finally, by reviewing technology roadmaps on wireless communication, it can be stated that there is a positive correlation between the requirements put forward by large industrial sectors and those arising in safeguards applications: notably, the need for interoperability with legacy systems (backward compatibility), for reconfigurable devices and for a complete control on network access. This provides a further motivation to believe that safeguards will be in a position to take advantage of technologies and concepts that are being developed in these directions.

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Ultra-Low-Level Measurements of Argon, Krypton and Radioxenon for Treaty Verification Purposes

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Abstract

Various noble gases are created in nuclear processes like burn-up of nuclear fuel, target irradiation and nuclear explosion. Being chemically inert, they won't react with the ambient environment or deposit on the ground once entered into the atmosphere but keep on travelling and only disappear due to radioactive decay. They are, therefore, very good tracers for revealing specific nuclear activities and can help in verifying non-proliferation treaties.

Krypton-85 and radioxenon isotopes are anthropogenic isotopes produced through fission of uranium or plutonium. The analysis of krypton in the atmosphere could help, e.g. in verifying compliance with the Nuclear Non-Proliferation Treaty by monitoring nuclear fuel re-processing activities. The detection of the radioxenon isotopes could give indications e.g. on a nuclear explosion, clandestine nuclear reactors or other violations of non-proliferation treaties.

Argon-37 is an anthropogenic isotope produced when e.g. fission neutrons react with calcium in rock. Its identification in the lower troposphere or in soil gas can be an indication for the detonation of a nuclear device and can be used to verify the Comprehensive Nuclear Test-Ban-Treaty e.g. during an on-site inspection.

Other noble gases like argon-41 and various short-lived krypton isotopes may be used for nuclear safety monitoring or reactor operation surveillance.

This paper will describe how these noble gases are created, measured at ultra-low sensitivity level and used to trace back a violence of treaties dealing with nuclear arms control and non-proliferation and propose additional applications of these new ultra-low environmental measurement techniques.

Keywords: treaty verification; environmental monitoring; radioxenon; noble gas; low-level measurements

1. Introduction

In the world of today, more and more sensitive methods have to be used and are being developed to deal with the threat of nuclear proliferation, nuclear terrorism and nuclear arms. It can be expected that a possible violator tries to hide these intentions and the clandestine preparation facilities. Traces of emissions originating from these processes may provide key information to reveal hidden activities. Therefore, monitoring of the atmosphere and environment in general is of vital importance for various treaty verification purposes.

Since uranium and plutonium are the key components of the nuclear reactions related to fission, their behaviour need to be known for nuclear non-proliferation as well as in monitoring nuclear explosions. In the burn-up of nuclear fuel and in the nuclear explosions two sources of radioactive material are generated:

- Fission products: these are direct products from the nuclear fission. Even when remotely measured, they may give information on the material used in the core of the nuclear device;

- Activation products: neutrons produced in the fission interact with the surrounding materials and also the core itself. As a result, substantial part of the material gets radioactive due to neutron capture. Activation products may give a good indication of the environment where the fission took place. Further they contain information on which materials the device was made of.

Because in fission the nucleus to split in an asymmetric manner, the fission yield curve for these elements (mass of fission products versus atomic mass of the fragments) has two asymmetric peaks, one in the area zirconium through to palladium and another at xenon through to neodymium. The fission yield is a function of the fissioned nuclide and the incident neutron energy (except for the case of spontaneous fission). Figure 1 shows the typical
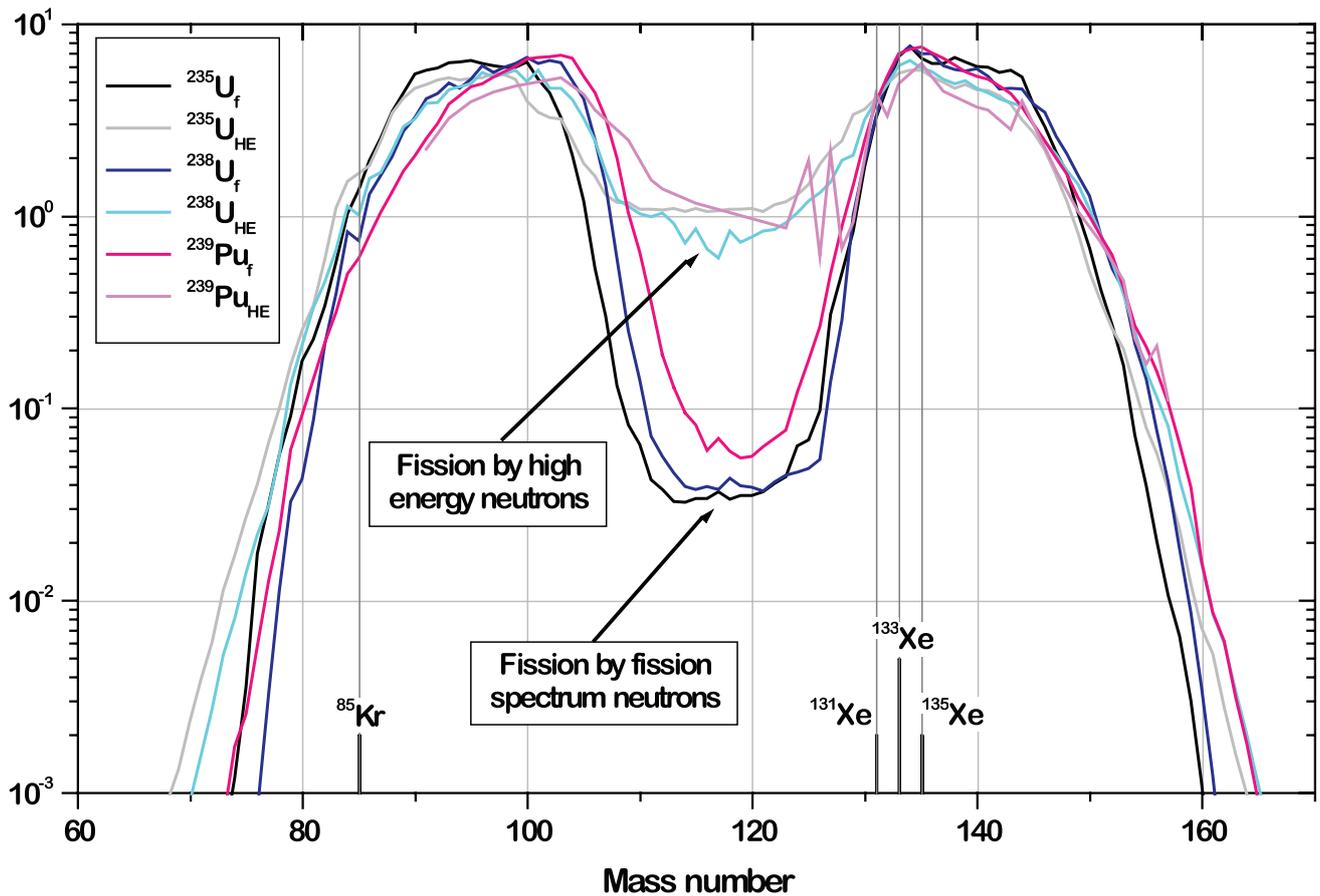
Figure 1: Fission yield in % for several nuclear explosion relevant nuclides: 235U, 238U and 239Pu, for fission induced by fission spectrum neutrons (f) and high energy neutrons (14.7 MeV) (he) respectively [1].

bimodal curve for fission-product yield. The curve shows that during fission, among others, relatively large quantities of radioxenon noble gases are produced (up to almost 7 % of the fission products). On the other hand, ^{85}Kr has only a fission yield of 0.3 % and less. Table 1 lists the cumulative fission yield for four relevant radioxenon isotopes.

2. Noble gases

The noble gases are: Helium (He), Neon (Ne), Argon (Ar), Krypton (Kr), Xenon (Xe), Radon (Rn) and Ununoctium (Uuo). They have a complete outer electron shell and are, therefore, chemically inert. Noble gases are inert and are therefore difficult to hide. For nuclear verification purposes, we will focus on the ^{37}Ar, ^{85}Kr and four radioxenon isotopes and isomers.

2.1. Argon-37

The atmosphere of earth contains around 0.93 % stable Ar. The name is derived from the Greek argos for "lazy" or "inactive". It was discovered by Lord Rayleigh and Sir William Ramsay in 1894 during an experiment in which they removed all of the oxygen and nitrogen from a sample of air. The melting point of argon is -189.35 °C and its boiling point is -185.85 °C.

The radioisotope ^{37}Ar ($t_{1/2}$ = 35.04 days) is produced in the atmosphere: ^{40}Ar(n, 4n)^{37}Ar. When ^{37}Ar decays (electron capture), it emits no photons but only electrons (Auger electrons).

It can also be the product of a reaction with fission neutrons on calcium (Ca): ^{40}Ca(n, α)^{37}Ar [2]. Ca is mostly contained in soils. The neutrons need to

Fission Product	Half-life	Time unit	^{235}U$_f$	^{235}U$_{he}$	^{238}U$_f$	^{238}U$_{he}$	^{239}Pu$_f$	^{239}Pu$_{he}$
^{131m}Xe	11.934	d	0.05	0.06	0.05	0.06	0.05	0.07
^{133m}Xe	2.19	d	0.19	0.29	0.19	0.18	0.24	0.42
^{133}Xe	5.243	d	6.72	5.53	6.76	6.02	6.97	4.86
^{135}Xe	9.14	h	6.6	5.67	6.97	5.84	7.54	6.18

Table 1: Cumulative fission yields in percent for six fission modes relevant to nuclear explosions, induced by fission spectrum neutrons (f) and high energy neutrons (14.7 MeV) (he) [1].

have an energy in the range of MeV to let the (n, α) reaction happen. Such neutrons are produced in a nuclear explosion. If, therefore, ^{37}Ar is found in soil gas, this is a certain proof of a nuclear explosion. Its concentration is strongly dependent on the calcium quantity of the environment of an explosion. After an underground nuclear explosion, ^{37}Ar can migrate to the surface into the atmosphere along faults and cracks, driven by e.g. the barometric pressure (low pressure weather systems) over several weeks and months.

2.2. Krypton-85

Around 0.114 % of the earth's atmosphere contains stable Kr. The name derives from the Greek kryptos for "concealed" or "hidden" and it was discovered in Great Britain in 1898 by Sir Ramsay and Morris Travers in residue left from evaporating nearly all components of liquid air. The melting point of krypton is -157.36 °C and its boiling point is -153.22 °C.

The radioisotope ^{85}Kr ($t_{1/2}$ = 10.76 years) is mainly produced during fission, although a small amount is produced in the atmosphere (from ^{84}Kr). It is a beta-emitter (99.56 %–maximum beta energy: 690 keV) but 0.43 % decays to an excited level, followed by a gamma ray of 514 keV.

Due to its relative long half-life, it remains for many years in used nuclear fuel or in soil after an underground nuclear explosion. It is released when nuclear fuel is dissolved for plutonium extraction or other purpose. There are no other relevant sources of ^{85}Kr than the atmospheric nuclear weapon tests in the past and the reprocessing now. Kalinowski [3] calculated that during the production of 1 kg of weapons grade ^{239}Pu (which contains less than 7% of ^{240}Pu) about 1.5 – 2.0 10^{13} Bq of ^{85}Kr is released. If ^{85}Kr detection system is sensitive enough, it could be used to monitor or discover reprocessing plants.

Further, due to its good geophysical properties, its long half-life and its chemical inertness, ^{85}Kr is used for several applications in geosciences, e.g. tracing the flow of ground- and ocean water.

2.3. Radioxenon

The earth's atmosphere contains approximately 0.009 % of stable Xenon (Xe). The name derives from the Greek xenon for "the Stranger". Xe was also discovered in 1898 by Sir Ramsay and M. Travers in residue left after evaporating liquid air. It is a heavy, odourless and colourless noble gas with

element number 54. Melting point of xenon is -111.7°C and its boiling point is -108.12 °C.

Naturally occurring xenon consists of seven stable and two radioactive isotopes (^{124}Xe and ^{136}Xe, both with very long half-lives). Beyond these stable forms, 20 other radioactive isotopes have been found. ^{131m}Xe, ^{133}Xe, ^{133m}Xe, and ^{135}Xe are some of the fission products of ^{235}U, ^{238}U and ^{239}Pu. The major part of radioxenon isotopes is manmade – however, the spontaneous fission of uranium in the nature produce very low levels of radioxenon.

As can be seen in the Table 1, ^{133}Xe has high production rates in ^{235}U, ^{238}U and ^{239}Pu fission. The half-life of ^{133}Xe is 5.2 days; this is perfect for detection systems since it is not accumulated in the atmosphere and it lives long enough to be detectable after atmospheric transportation to a monitoring station. This isotope is therefore typical detected in various environmental samples.

^{135}Xe has a very high thermal neutron capture cross section, so it can absorb thermal neutrons very well. As thermal neutrons are needed to maintain the nuclear chain reaction in a reactor, ^{135}Xe is a "poison" that can slow down the chain reaction or even stop it.

3. Ultra-low level measurement techniques

Radioactive noble gases can be extracted from the environment with high efficiency, as they are inert. On the other hand, they have low solvability and are present in the ambient nature in very low concentrations.

Many methods are used to measure radioactive noble gases. Among them are Low-Level Decay Counting (LLC), Mass Spectrometry (MS), Accelerator Mass Spectrometry (AMS), Resonance Ionization Mass Spectrometry (RIMS), Atom Trap Trace Analysis (ATTA) and additionally for the photon emitters, gamma and beta-gamma coincidence spectroscopy [4; 5]. In the following we will focus on the most common techniques used for nuclear non-proliferation and nuclear explosion monitoring: LLC for ^{37}Ar and for ^{85}Kr and gamma and beta-gamma spectroscopy for radioxenon analysis.

Some systems have recently been designed for mobile noble gas collection and analysis (e.g. ARIX-III, MARDS and SAUNA-II OSI). The measurement techniques used to reach the required ultra-low activity concentration levels needed in mobile measurement systems requires that the systems are optimised for certain radioisotopes of interest. The techniques used with an emphasis on the

analysis of radioactive noble gases are briefly reviewed in this paper.

The unit of detectability, minimum detectable concentration (MDC), is defined as the smallest concentration of radioactivity in a sample that can be detected with a certain probability. When detecting the activity, one can define two different ways to make wrong conclusions:

- Erroneously detecting radioactivity, when in fact none was present (Type I error)

- Not detecting radioactivity, when in fact it is present (Type II error).

Improvement of detection capability and ability to make right conclusion are also key issues for verification work with ultra-low level measurement techniques.

3.1. Argon-37 measurement systems

The worldwide background of ^{37}Ar is very low. Therefore, special ultra-low level counting techniques are used for measuring the activity. The measurement of its low decay energy (2.8 keV) is done with special low-level gas proportional counters.

The only laboratory worldwide that can measure ^{37}Ar at ultra-low levels is situated at the University of Bern, Switzerland. This laboratory has ultra-low background measurement chamber 35 meters underground, and it is using the LLC method.

For the purpose of on-site inspections (OSI) in the framework of the Comprehensive Nuclear Test-Ban-Treaty (CTBT), the Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang, China, has developed the Movable Argon-37 Rapid Detection System (MARDS). This system extracts the argon from sampled air and measures the ^{37}Ar radionuclide with a gas proportional counter [6].

3.2. Krypton-85 measurement systems

The U.S.A. used the ^{85}Kr detection technique already in 1951 to monitor the Soviet production of Pu. Later they also monitored other countries (Operation Bluenose). Air was collected in gas bottles, which were shipped to a laboratory for measurement.

As its gamma emission is too small to be measured in environmental samples directly, it is a challenge to measure the activity concentration of this isotope with a good sensitivity, as the samples may be small and the measurement time can be limited. A commonly used method is the LLC. In this method the krypton is first freezed out and then measured in a gas proportional counter [7]. This measurement

should ideally be performed in a low-background environment.

The Noble Gas Laboratory of the German Federal Office for Radiation Protection (BfS) has analysed among other things ^{85}Kr in the environment since the early 1970's. Bieringer and Schlosser describe in [8] their routine analysis the following steps:

1. Enrichment, purification and separation of the noble gas fractions by cryogenic adsorption and desorption and gas chromatography;

2. Measurement of the integral beta activity by gas counting in proportional counters and determination of the stable krypton volume by gas chromatography.

New automated and mobile systems that has a detection capability of ^{85}Kr down to 0.1 Bq/m^3 with a 6 hour measurement time, like e.g. the French SPAARK system (Système de prélèvement et d'Analyse Automatique du Radio Krypton) [9].

3.3. Radioxenon measurement systems

The first radioxenon measurements date back to the second world war, when American airplanes flew low over Germany, sampling air and trying to find traces of a German nuclear reactor and weapons programme [10]. During the nuclear testing era, ^{133}Xe was measured both onsite and offsite by the tester. Because of the detection capability of the early equipment, the traces of ^{133}Xe were detected only if the nuclear test was atmospheric or badly contained underground test.

The International Monitoring System (IMS) is the monitoring system that will verify the CTBT [11]. According to this Treaty there will be at its Entry Into Force (EIF) 40 stations worldwide capable of measuring the relevant Noble Gases [12]. The other technologies used for its verification are radioactive particles, seismology, hydroacoustic- and infrasound monitoring. In addition to this, the radioactive substance detection requires atmospheric transport modelling (ATM). Since commercial noble gas systems with suitable detection capability were not available, the Preparatory Commission (PrepCom) of the CTBT Organisation (CTBTO) tasked the Provisional Technical Secretariat (PTS) of the CTBTO in 1999 to perform an International Noble Gas Experiment (INGE) according to the required specifications of the noble gas monitoring.

Four countries announced their willingness to provide radioxenon sensors: the USA made a system called ARSA, Russia constructed ARIX, Sweden built SAUNA and France offered the

SPALAX system. The design criterion for all of them is that the MDC of ^{133}Xe should be 1 mBq/m³ or less for a 24-hour sampling period [13]. Three of the systems, the ARSA, the ARIX and the SAUNA, are using very similar measurement techniques and produce two-dimensional beta-gamma coincidence spectra [14;15;16]. The SPALAX system is based on high-resolution gamma spectroscopy [17]. The original ARIX system was based on beta-gated gamma spectroscopy [18], until this technique was modified to beta-gamma coincidence spectroscopy in early 2007.

For the purpose of on-site inspections, mobile versions of the ARIX and the SAUNA systems have been developed. These systems have proven to be operational during a field experiment set up in Seibersdorf, Austria, in the summer of 2006. The Swedish mobile SAUNA-II OSI system has also been deployed in the Republic of Korea, immediately after the announced nuclear explosion of the Democratic Peoples Republic of Korea, to clarify whether the explosion was in fact a nuclear weapon test or not [19].

The BfS e.g. applies the integral counting method described above with krypton also for radioxenon measurements. All xenon isotopes in the sample are determined simultaneously. [131m]Xe and [135]Xe activities can be calculated with decay rates of these isotopes by measuring the sample in time-slices.

3.3.1 Sampling and purification of xenon

The noble gas systems developed to measure the four CTBT relevant isotopes at ultra low level are based on similar collection principles. Air is sampled at "high" volume with an air flow that has to be larger than 0.4 m³/h. This air is cleaned: aerosols, water, Rn, Ar, N_2, O_2, CO_2, etc. are removed, among others with filters and by heating. The next step is the extraction of xenon gas from the air. This is performed with high efficiency by adsorption of xenon onto charcoal followed by thermal desorption of the xenon and depending on which system, also with molecular sieve columns. The stable xenon volume of the concentrated gas is quantified by means of a gas chromatograph.

3.3.2. Nuclear measurement of radioxenon isotopes

After a 12 hour cycle, between 0.5 and 3 ml of stable xenon has been extracted, which is enough for a low level nuclear measurement. This is based on one of the following two methods: two-dimensional beta-gamma coincidence spectroscopy or high-resolution gamma spectroscopy.

The β-γ detector has a sodium-iodine (NaI) crystal with a drilled hole, where the gas flows in. The hole accommodates a plastic scintillator cylinder. Gamma pulses are counted through photomultipliers in both of the ends of the crystal and beta pulses are counted with the scintillator cylinder. The electronic system counts the gamma, the beta and the coincidence pulses typically 12 hours with noble gas sample inside. Before each measurement, a quality control source (e.g. [152]Eu) enters the cell and is measured. As some xenon diffuses into the plastic scintillator, a gas background is measured for 11 hours to count this possible memory effect of a previous sample.

The γ detector consists of a p-type broad energy High Purity Germanium (HPGe) detector. The detector type has minimal dead layer despite it is of p-type. The gas flows in a sample cell, which is made of low background aluminium. The cell is located on top of the germanium crystal. Some measurement systems have carbon fibre window to provide improved X-ray detection. The gas sample is typically measured for 24 hours. A quality control source is mounted above the cell. This source contains a mixture of radioisotopes that emit gamma lines at other energies than radioxenon does. The purpose of this source is to check the stability of the detector.

The xenon sample is archived in separate archive bottles, one for each sample. After 5 – 7 days, these bottles are emptied, flushed with a clean gas and they can be re-used.

CTBTO is using remote analysis of the measurement results. After the measurement is done and spectral data saved, it is transmitted through PTS' Global Communication Infrastructure to the data centre for analysis, review and final conclusions. [20]

3.3.3. Spectral analysis of radioxenon isotopes

The four major xenon isotopes emit all photons (X-rays and/or gamma rays) in coincidence with beta and conversion electrons. X-rays are at 30 keV (with slight shifts caused by the different nuclear mass of the various isotopes) and have a total branching ratio of about 50%, except for [135]Xe, which has just a 5% X-ray branch. The strongest associated conversion electrons in coincidence with the X-rays are 129.4, 198.7, 45.0, and 213.8 keV for [131m]Xe, [133m]Xe, ^{133}Xe and [135]Xe, respectively. Other strong coincident decay modes are up to 346 keV energy beta decay of ^{133}Xe in association with a 81.0 keV gamma decay, and up to 901 keV energy beta decay in [135]Xe, which is followed by a 249.8 keV gamma ray (see Table 2).

Isotope	Energy X-ray [keV] ($K_{\alpha1}$ and $K_{\alpha2}$)	Intensity* [%]	Energy γ-ray [keV]	Intensity [%]
^{131m}Xe	29.62	44.4	163.930	1.91
^{133m}Xe	29.62	46.1	233.22	8.2 [22]
^{133}Xe	30.80	40.9	80.997	38.0
^{135}Xe	30.80	2.1	249.77	90.0

Table 2: The four relevant radioxenon isotopes and their most intense γ-ray and X-ray (from the Evaluated Nuclear Structure Data File [23]).
* These values are the weighted averages of the $K_{\alpha1}$ and $K_{\alpha2}$ X-rays. The intensities are the sum of these two K_{α} lines

In gamma and beta-gamma spectroscopy, ^{133}Xe and ^{135}Xe isotopes are identified by their photon peaks. If the isotopes ^{131m}Xe and ^{133m}Xe have a low activity in a sample, the photon peaks may be below the detection capability of the measurement systems Thus, only the 30 keV X-ray peak may be visible. The beta signal can give the missing information to calculate the activity of the metastable isotopes. If the beta-signal is not measured (e.g. for the SPALAX system), the analysis is still possible through a complex gamma peak and x-ray peak deconvolution together with a half-life analysis of all the preliminary spectra measured on the sample. This method has been developed at the PTS [21].

4. Environmental monitoring of noble gases

Environmental monitoring is a powerful tool in detecting low levels of radio-isotopes in the environment. The isotopes of interest can be found in soil and vegetation, in the hydrosphere and the atmosphere. We will concentrate on monitoring of the atmosphere. To be able to perform environmental monitoring with the scope of finding anomalous signals that could reveal important information, several factors have to be known and to be taken into account while evaluating the results of the monitoring. The regional background of the selected radionuclide is important as well as climatological and meteorological behaviour at the sampled location.

4.1. Environmental background

To monitor the environment for certain radioactive noble gases, one has to be able to distinguish the real signal from a background signal. The noble gases of interest have following global background characteristics:

- Almost all ^{37}Ar is natural;
- Most of the ^{85}Kr is anthropogenic all over the world;
- Nearly all radioxenon is anthropogenic and its concentration can be regionally different.

^{37}Ar background is very low and rather stable (in the order of mBq/m^3).

Due to its long half-life, ^{85}Kr, has a large background in the whole northern hemisphere. Its worldwide background started increasing dramatically by a factor of one million after the first nuclear weapon tests in the atmosphere took place in the late forties and it is continuing to increase with the installation of large reprocessing plants.

The worldwide background of ^{85}Kr is currently between 1.0 and 1.4 Bq/m^3 [24]. This value varies with seasonal influences, atmospheric dilution and large releases at reprocessing plants. Due to dence nuclear installations, the concentration is higher at the northern hemisphere.

Although radioxenon isotopes have a shorter half-life, they are produced at most nuclear facilities and can therefore be found in wide regions around where nuclear facilities are. To distinguish clandestine nuclear facility or a nuclear explosion from other signals, the worldwide background (activity concentrations and also activity ratios) has to be studied carefully. The background of radioxenon and the ratio of different radioxenon isotopes is depended from several factors and sources and can vary over a few orders of magnitude. The different sources can be:

- Nuclear Reactors: mainly ^{133}Xe
- Fuel reprocessing plants: mainly ^{131m}Xe
- Hospitals: mainly ^{133}Xe and ^{131m}Xe
- Nuclear Explosions: mainly ^{133}Xe, ^{135}Xe and ^{133m}Xe

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) reports regularly on emissions from nuclear reactors worldwide [25]. The report contains global noble gas release inventory and in several cases it has also the radioxenon isotope 133 is listed separately. Kalinowski et al. [26] have collected a database of worldwide radioxenon release data from various sources. Table 3 gives an overview of the order of magnitude of radioxenon release from different kind of facilities.

Type of facility	Order of magnitude of radioxenon release
Hospitals	~ 10^3 Bq
Research laboratory	~ 10^6 Bq
Nuclear power plants	~ 10^9 Bq
Radiopharmaceutical plants	~ 10^{12}–~ 10^{13} Bq
1 kton nuclear explosion underground	~ 10^{13}–~ 10^{15} Bq
1 kton Nuclear explosion atmospheric	~ 10^{16} Bq

Table 3: Order of magnitude of radioxenon release from different nuclear facilities and events

To understand the radioxenon background, several statistical studies have been or are being performed with the experimental stations of the INGE network. During 2007, 18 systems will be measuring radioxenon isotopes in different parts of the world (see Table 4). Some of these stations have been operating already longer than five years. Based on current experience the radioxenon background can be categorised into four groups:

- Radioxenon is not expected: no radioxenon isotopes present (e.g. at Tahiti in the Southern Pacific) [27];

- Regular but low radioxenon background of one or two isotopes: regular presence of ^{133}Xe and or ^{131m}Xe at very low concentrations (less than 1 mBq/m^3) (e.g. on the Arctic station of Longyearbyen, Spitsbergen) [28];

- Regular radioxenon background of ^{133}Xe (~ 1–100 mB/m^3) and occasionally other isotopes at low level (e.g. in the European station on the Schauinsland mountain in the Black Forrest, Germany) [29];

- High radioxenon background with many isotopes: all isotopes are regularly present at different activity concentrations (up to few Bq/m^3) (e.g. the station of Ottawa, which is surrounded by nuclear power industry and a large radiopharmaceutical production facility) [17].

It has been shown that the environmental concentration of ^{133}Xe in Central Europe is few mBq, in Scandinavia around 10 % less and in the high Arctic (Spitsbergen) another 10 % less [30]. Further, there was a 20 fold decrease of the environmental radioxenon activity concentration in the late 1980's, which happened due to improvements in the nuclear fuel rod cladding and reactor containment systems and longer decay times before the noble gases are released into the atmosphere. [31]

As can be seen in Table 4, the global radioxenon background has not been characterized in many areas containing nuclear facilities and thus radioxenon emissions. Therefore, more radioxenon background studies are needed.

4.2. Radiopharmaceutical radioxenon sources

Radioactive pharmaceuticals are used in nuclear medicine for diagnosis (e.g. imaging) or for treatment. Common isotopes are e.g. ^{99m}Tc, ^{131}I and ^{133}Xe. ^{99m}Tc is used a lot in pharmacy due to its half-life of 6 hours and low gamma energy at 140 keV, ^{131}I is used widely in the world for thyroid treatment. ^{133}Xe (half-life of 5.2 days and 38 % intensity 81 keV photon energy) is used for measuring the physiological parameters of lung ventilation and to image the lungs. It is also often used in an isotonic solution to image blood flow, particularly cerebral blood flow.

^{99m}Tc is the daughter nuclide of ^{99}Mo ($t_{1/2}$ 65.94 h). The most common way to produce the fission product ^{99}Mo is the irradiation of highly enriched uranium (HEU, up to 95 % of ^{235}U). It can also be produced by using low enriched uranium (LEU, less than 20 % ^{235}U) or via neutron activation (n,γ reaction) of ^{98}Mo in a high neutron flux reactor. After the irradiation, ^{99}Mo is separated chemically and then distributed to the end customer, e.g. hospitals. In the hospitals, ^{99m}Tc is extracted just in time before being used on a patient.

When fission is used for the production of radiopharmaceuticals, also radioxenons are produced. They will escape into the atmosphere, especially during the chemical process producing a high radioxenon background [32]. First measurements and preliminary estimates using ATM indicate that these sources might dominate the radioxenon background, as their releases can be up to three orders of magnitude above the ones from nuclear power plants.

4.3. How noble gases enter the atmosphere

4.3.1. Release from a nuclear facility

Fission product noble gases are created within the fuel material of nuclear reactors. There can be cracks in the cladding (the outer layer of the fuel rods, e.g. Zircaloy), which will allow some noble

gases to leave the fuel rods and enter the primary cooling material (e.g. water or gas). More quantities can be released during start-up and shut-down of the reactor, due to thermal stress of the cladding material in these phases. Further, some noble gases are created from fission of traces of U or Pu in cooling material itself. Rarely, noble gases can escape the fuel due to a process disturbance or an accident. The isotopic composition of the release can be very different depending on in what kind of circumstances and how fast the release is occurring. Also depending on the containment, the emissions may stay variation of time in the release pathway, during which they are decaying. Some facilities use special retention lines, where high radioactive gases decay up to several tens of days, before they enter the stack to leave the facility and enter the atmosphere. Reprocessing plants release noble gases during the processing of nuclear fuel, most of them during the dissolving of the fuel. Also in radiopharmaceutical plants most of the releases occur during the chemical process (see 4.2). All these delaying factors have to be taken into account when ratios of environmental radioxenons will be studied.

Appelhans and Turnbull [33] have calculated in detail the release fraction of noble gases in light water reactors, while Kalinowski and Fister [34] have simulated radioxenon ratios of light water reactors under different circumstances.

4.3.2. Source term of radioxenon in a nuclear explosion

During fission of uranium or plutonium in a nuclear reactor, thermal (slow) neutrons are used, whereas during a nuclear explosion the great amount of fission is induced by fast neutrons. Most of the nuclides in the explosion device undergo fission within a microsecond.

There is little time for activation build-up in a nuclear explosion whereas there is sufficient time for production of many activation products in a nuclear reactor. These differences produce different radionuclide abundances. Since a nuclear blast produces different radionuclide abundances, nuclide ratios may be used for source identification.

The energy produced in a one kiloton (kton) nuclear explosion is equivalent to an explosion of 1000 tons of TNT, which equals 10^{12} calories = 4.2 10^{12} Joules.

The average total energy produced in fission of one ^{235}U atom is 200 MeV = 3.2 10^{-11} J (with 1000 MeV = $1.602.10^{-10}$ J), the average total energy released in fission of one plutonium-239 atom is 210 MeV = 3.5

10^{-11} J. This energy takes the form of the fission fragments, instantaneous gamma-ray energy, kinetic energy of fission neutrons, beta particles from fission products, gamma rays from fission products and neutrinos from fission products. About 180 MeV is immediately available as energy from each fission event, which means that there are around 1.45 10^{23} fissions per kton. With

$$A = \lambda . N(t) = \frac{\ln(2)}{t_{1/2}} . N(t)$$

A = activity [Bq]

λ = decay constant

$N(t)$ = number of atoms

$t_{1/2}$ = half-life [s]

an upper and lower emission value can be calculated. According to Table 1, ^{239}Pu$_{he}$ has the lowest cumulative fission yield for ^{133}Xe (4.86 %) and ^{238}U$_{he}$ has the highest (6.02 %). Therefore, depending on the fission material inside the nuclear device, between 1.08 10^{16} Bq and 1.33 10^{16} Bq of ^{133}Xe will be released in a 1 kton nuclear explosion.

However, from the mass 133 isotopes that are produced during the explosion, the ^{133}Xe concentration is initially very low. De Geer [pers. comm.] calculated the dynamics of the isobar chains for the four considered radioxenon isotopes. After the explosion of a ^{239}Pu device used, ^{133}Xe reaches its maximum concentration (as calculated above) after 2.8 days due to in-growth.

4.3.3. Release from underground nuclear explosions

For an atmospheric or near surface nuclear explosion, all the debris is in the atmosphere and can be more easily measured by e.g. a station of the particulate radionuclide component of the IMS. In this case, radioxenon stations give only little added value. If, however, the explosion is underground or deep under water, only noble gases might leak out and the radioxenon stations of the IMS will be the only ones that will be able to proof that the explosion was nuclear [35; 36].

After the Partitial Test Ban Treaty got into force in 1963, most nuclear explosions were performed underground in drilled vertical holes or in mined tunnels. The goal of the state performing the test was to acquire the experimental information of the nuclear device for and at the same time contain the explosion fumes, i.e. prevent that any radioactive material would reach the atmosphere.

The time a gas needs to reach the surface is dependent on its diffusivity, the power of the explosion and on the underground environment (amount of fractures, humidity, geological structure and faults etc.).

Schoengold et al. [37] reported that up to 20 Bq/m^3 of ^{133}Xe could enter the atmosphere after an underground explosion at the Nevada Test Site, USA. Often, however, the activity concentration of ^{133}Xe was not reported after a nuclear test as it was below the detection capability of the equipment used that time.

Dubasov [38] reported on releases of ^{133}Xe from underground tests in e.g. the Novaya Zemlya Archipelago (Arctic Russia) in the late eighties, measured in subsoil gas and in the atmosphere. Some atmospheric samples contained up to 620 mBq/m^3. A MDC between 150 – 400 mBq/m^3, 135 days after underground 30 – 150 kton tests was calculated for the equipment used at that time. The activity concentration in subsoil gas samples was found to be around 2000 times higher than the atmospheric concentrations measured. In Kurchatov, around 100 km from the test site, also ^{85}Kr with 20 times higher than continental background was measured, with a MDC of 3.7 Bq/m^3. All releases of noble gases below the MDC level where declared to be complete contained explosions. In another report, Dubasov [39] informs about noble gas releases in the Semipaltinsk test site (now Kazakhstan) between 1961 and 1990. There, the MDC for ^{133}Xe was around 400 Bq/m^3, whereas actual equipment measures close to 0.2 mBq/m^3.

The Soviet Union made 8 tests with a total yield less than with 150 kt in a tunnel on the Novaya Zemlya Northern Site on the 20 October 1990. These underground test were detected in Sweden with radioxenon measurements, approximately 24 mBq/m^3 of ^{133}Xe was detected by after these tests [De Geer, pers. comm.].

In 1996 a Non-Proliferation Experiment (NPE) was performed. A conventional explosion of 1 kton, was detonated in Rainier Mesa (Nevada Test Site) at 400 m depth. It included also sulphur hexafluoride (SF$_6$) gas and ^{3}He to simulate argon and radioxenon. Carrigan et al. [40] concluded that ^{133}Xe would be detectable 50 days after detonation, whereas ^{37}Ar would need 80 days to reach the surface. The main mechanism driving the release in this case is atmospheric pumping. The difference of the release time is due to the different physical properties (diffusivity) of these molecules–the most diffusive entered the atmosphere the latest because they had gone deeper into cracks and were therefore better hidden than the lower diffusive molecules. According to Carrigan et al., after a 1 kton fission detonation the total release of ^{133}Xe could be around 9.7 10^{12} Bq in a period of weeks till months after the detonation due to seepage.

Releases of radioactive material following an underground nuclear test are generally categorized as follows:

- Unintentional release of radioactive material to the atmosphere due to failure of the containment system (0–100 % of the created noble gases (primarily ^{85}Kr and ^{133}Xe) could enter the atmosphere);

- Prompt venting due to high pressure of the explosion and other dynamic effects (pushes gas through cracks and fissures in the bedrock, ~ 10 %);

- Venting due to opening of tunnels to measure the detonation effects or due to removal of the measurement materials. This can happen days till weeks after the event (controlled tunnel purging)

- Drilling of holes etc. (operational releases);

- Natural atmospheric removal, low pressure is pumping out the gases stored in the fissures and cracks under ground (late-time seeps due to atmospheric pumping) (~ 1 %).

Immediately after an underground nuclear explosion, the materials around the device are vaporised due to the enormous heat. When the heat lowers down, vaporized gases condensate to particles, this process is complex and involves many chemical and physical processes. Because the chemical and physical properties of the materials change as a function of time, the materials escaping from the cavity and remaining there may differ. Some substances stick faster to the wall of the cavity, whereas others are more volatile and can move a certain distance in cracks before they condense. This has also an effect on the gases that are created in the explosion, especially if the decay products are changing the phase from solid to gas (e.g. ^{133}I à ^{133}Xe).

4.4. From a source to a detector

In general, the probability that a detection system can measure a signal from nuclear activities is depended from:

- the amount of released noble gases;

- the atmospheric dispersion between the source and the monitoring system;
- the MDC of the measurement system;
- the local environmental background.

Since noble gases are chemically inert, they do not react with particles or water vapours of the clouds during their atmospheric transport. The deposit on the ground does not occur either, but their concentration in the air shall decrease due to radioactive decay and dilution. They are, therefore, very good tracers for finding specific nuclear activities, like i.e. nuclear explosions.

Once an environmental noble gas measurement system has identified certain relevant radionuclides, it is of key importance to find the possible release point of these measured nuclides. To perform these calculations, different atmospheric transport models (ATM) can be used. The PTS of the CTBTO uses routinely models based on Hysplit or Flexpart [41; 42]. These models benefit form possible information of event time that can be available for example through seismic, infrasound or hydro-acoustic detection.

There can be two scenarios: the geographic location of the source is thought to be known or it is unknown.

In the case the source is thought to be known, ATM could strengthen a hypothesis or could exclude regions where a release probably took place. An example is a known facility that performs undeclared activities or in the case of nuclear explosion monitoring, waveform signals that indicate the location, depth and time of an explosion. It should be noted that tele-seismic waveform signals cannot distinguish between a conventional chemical or a nuclear explosion.

The case that the source location is unknown is more complex, especially as the calculated possible source region (PSR) can be large (up to several ten thousand of km^3). Methods to reduce the PSR are e.g.

- calculating ratios if different radioxenon isotopes have been measured and determine the time of the event or the possible source (e.g. a nuclear reactor in equilibrium emits different radioxenon ratios than at start-up or shut-down or than a nuclear explosion). Ratio calculations are, however, only possible for radioxenon isotopes if multiple isotopes are detected. This method does now work with argon or krypton;

- use information from different monitoring stations which have measured a signal that could originate from the same source;

- use the different signals from several days, measured at the same station.

It should be noted that the traces of certain radioactive noble gases measured may have very distinct history – they can be released as a puff or over a longer time, they have travelled a while and decayed during that time period. Further they diluted in the atmosphere and probably were mixed with air masses that might also contain noble gases from other sources. Also, since the samples are collected in 8-24 hours shifts, the exact time and duration when the measurement station is exposed to passing noble gas cloud is not known. All these factors have to be taken into account when data are interpreted. The more samples are measured with a short time period each, the better the possibilities are to find its source of origin, as the signal will not be diluted with air that contains only background activity.

4.5. Noble gas measurement networks

The only treaty that currently uses environmental monitoring of atmospherically transported substances for its verification is the CTBT, which monitors radionuclide particulates and radioxenon isotopes. All other networks are national or academic ones.

4.5.1. Global Krypton-85 networks

Several networks monitor worldwide ^{85}Kr. One of them is the German Integrated Measuring and Information System (IMIS), which operates with 15 stations worldwide [8]. The air is sampled at the stations for about one week with a collection volume of 0.06 m^3/h. Krypton is collected by adsorption on active charcoal at -197 °C (using liquid nitrogen) and then shipped to Freiburg, Germany for analysis.

4.5.2. The network of the International Noble Gas Experiment

As described in 3.3., four automated systems were developed in the framework of INGE. In 2000 these four systems were tested together for several months in parallel in Freiburg, Germany [43]. Afterwards, these four prototypes were installed at IMS sites in Guanghzou (China), Buenos Aires (Argentina), Spitsbergen (Norway) and Papeete (Tahiti). In the meantime, industrial versions have been developed and more stations are now installed worldwide, as is shown in Table 4.

Country	Station location	Start date	System type
Argentina	Buenos Aires	June 2005	ARIX-II
Australia	Darwin	Sept. 2006	SAUNA-II
Brazil	Rio dei Janeiro		u.p.
Canada	Ottawa	Nov. 2001	SPALAX
Canada	St. Johns	March 2006	SPALAX
Canada	Yellowknife	Aug. 2003	SPALAX
China	Beijing	Dec. 2006	SPALAX
China	Guangzhou	mid 2007	SAUNA-II
France	Cayenne (French Guinea)	mid 2007	SPALAX
France	Papeete (Tahiti)	May 2002	SPALAX
France	Réunion		u.p.
Germany	Schauinsland	Feb. 2004	SPALAX
Japan	Takasaki	Nov. 2006	SAUNA-II
Mongolia	Ulaanbaatar	June 2006	SPALAX
New Zealand	Chatham Island	mid 2007	SAUNA-II
Norway	Longyearbyen (Spitsbergen)	Sep. 2001	SAUNA-II
Panama	Panama City	Jan. 2007	SPALAX
Russian Federation	Dubna	Sept. 2006	ARIX-II
Russian Federation	Ussuriysk		u.p.
Sweden	Stockholm	Aug. 2005	SAUNA-II
U.S.A.	Charlottesville	mid 2007	SAUNA-II

Table 4: The INGE network radioxenon stations that are or will be operational in 2007.
The start date column provides the date when first spectra were send to the PTS. Currently there are no
ARSA systems measuring in INGE. Ottawa is the only non-IMS operated station and is a national contribution
of Canada. u.p.: under procurement.

The INGE network has some unique features:

- high time resolution: previous measurement campaigns sampled air for weeks or months before the noble gas samples were measured, whereas the INGE stations sample between 8 and 24h per cycle. With such short sampling time ATM can be used to calculate possible source regions;

- geo-resolution: the 40 stations (with the possibility to be increased to 80 after entry into force of the CTBT) are distributed in such way that the traces of a 1 kton nuclear explosion can be measured within 2 weeks, which means that signals from an event can be monitored still at distances of several thousand of km.

- very low detection capability: down to 0.2 mBq/m^3 for ^{133}Xe for a 12 hour measurement;

- automated systems that can be deployed at very remote places without the need of local technically highly skilled personnel.

The Democratic PeoplÈs Republic of Korea's announced nuclear explosion was a good test case where a long distance radioxenon signal was measured in one of the INGE stations, in Yellowknife in the north of Canada [44]. The IMS seismic signal gave a correct indication of the time and place the explosion took place. The forward ATM calculations predicted then, using the before mentioned source term for a 1 kton nuclear explosion, two distinct ^{133}Xe signals in Yellowknife between two and three weeks after the explosion with very low concentration. This two peak signal was then indeed measured at the predicted time and activity concentration. Backtracking ATM calculations are consistent with the assumption that the measured ^{133}Xe signal could have originated from the Korean peninsula.

5. Verification applications

This chapter will describe the applications of the discussed noble gas measurements, in the light of non-proliferation treaties and weapons detection.

The goal of the Non-Proliferation Treaty (NPT), opened for signature on 1 July 1968, is to limit the spread of nuclear weapons. The Euratom Treaty, signed in 1957, established a nuclear material control system and assigned to the European Commission the responsibility of satisfying itself

that fissile nuclear materials (e.g. U and Pu) are not diverted from their intended use as declared by the users. It doesn't foresee, however, environmental sampling as a verification method. The Comprehensive Nuclear-Test-Ban Treaty forbids all nuclear explosions and the Fissile Material Cut-off Treaty would ban the production of fissile material for nuclear weapons.

A non-treaty verification application of radioxenon measurements could be the monitoring of the noble gas activity concentration close to nuclear installations from the point of view of quality of safety.

5.1. Non-Proliferation Treaty

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) has three pillars: non-proliferation, disarmament and the right to use nuclear technology peacefully. It entrust the International Atomic Energy Agency (IAEA) as its nuclear inspectorate.

The IAEA has specific roles, among them the international safeguards inspectorate which verifies that member states are not diverting nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices, i.e. that they comply to the NPT. Under a Comprehensive Safeguards Agreement, which is signed with each member state, the IAEA has the task to verify the declared nuclear material and nuclear material related activities of the country.

Iraq's clandestine nuclear weapons programme in non-declared facilities showed the limits of traditional safeguards. Therefore, member states added in 1997 measures to strengthen the IAEA's inspection capabilities. These are incorporated in the "Additional Protocol" to the NPT, which is a legal document complementing comprehensive safeguards agreements. The measures enable the IAEA not only to verify the non-diversion of declared nuclear material but also to provide assurances as to the absence of undeclared nuclear material and activities in a State. This Additional Protocol brought e.g. a legal basis for environmental sampling to verify compliance with the NPT. It describes wide-area environmental sampling (WAES), which is would allow the Agency to take samples also far away from the declared facilities. Its art. 9, however, stipulates that such techniques and the procedural arrangements related to WAES have to be agreed first by the IAEA Board of Governors.

Some possibilities where WAES could discover illegal activities are e.g. detection of non-declared

reactor operations, of hidden reactor operations and of stored fissile material.

Since ^{85}Kr escape from dissolved nuclear fuel during the re-processing activities, it could serve a an indicator if a known reprocessing plant is still operational or not. Measurements in or close by the plant can provide evidence of such activities. Mobile environmental monitoring of ^{85}Kr can also identify clandestine Pu separation facilities. The detection probability using remote environmental measurements, according to a study made by Kalinowski et al. [2004] near Karlsruhe, Germany of ^{85}Kr as an indicator for plutonium separation, found the following detection rate for the separation of 4 kg of plutonium per week:

- 80% to 90% at the distances < 1 km

- 70% at 5 km

- 40% at 39 km

- 15% at 130 km

Currently, radioxenon monitoring is mainly used to monitor nuclear explosions from a long distance or to identify traces of an underground nuclear explosion by sampling underground gas during an on-site inspection, both to verify the CTBT. However, as signals of radioxenon point to nuclear activities, other applications could be:

- verification of known nuclear reactor operations: measuring the radioxenon isotopical ratios can give information on specific reactor operations, e.g. the ratios change considerably during start-up and shut-down [33]. However, the measurements are typical for each facility and have to be performed in the vicinity of the reactor as they as they depend e.g. on the presence of facility design and delaying the emissions to the environment. Further, the measured air should not get mixed too much with the radioxenon background, in order not to loose the unique signal;

- detection of hidden reactor operations: the air in the vicinity of nuclear power plants can have a concentration of a few Bq/m^3 of ^{133}Xe. If the regional radioxenon background is known, hidden reactor operations can be found. However, the measured signals should be validated with ATM to confirm that the signal was not brought to the noble gas measurement station from a long distance. Measurements with a mobile system, however, could be performed at different locations, to get certainty of the results. One should also note that legitimate nuclear activities may also cause emissions, therefore, the nuclear

activities close to the inspection area should be characterized and monitored in the same time.

A non-environmental measurement application of radioxenon noble gas could be the verification of stored fissile material via measurements of radioxenon isotopes from spontaneous fission in the material. 1 kg of weapons grade plutonium will have in equilibrium an activity of around 2 kBq. Only a part will be released in the air, which still can be in the order of Bq, which is well above the normal local background.

5.2. Comprehensive Nuclear Test-Ban-Treaty

The CTBT is a key instrument of the international nuclear non-proliferation and disarmament regime built around the non-proliferation of nuclear weapons. Its total ban of any nuclear weapon test explosion will constrain the development and qualitative improvement of nuclear weapons and end the development of advanced new types of these weapons.

Its article 1 points out the essence of the Treaty:

• Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control.

• Each State Party undertakes, furthermore, 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 objective of the IMS is, according to the CTBT: "…At least 90% detection capability within 14 days after a nuclear explosion in the atmosphere, underwater or underground for a 1 kton nuclear explosion". A network is being build of waveform monitoring stations (seismic (170 stations), hydroacoustic (11) and infrasound (60)) and radionuclide stations (radionuclide particulate (80), noble gas (40) and certified radionuclide laboratories (16)). The radionuclide sampling sites have been defined in an appendix of the Treaty.

In the past nuclear explosions in the atmosphere, or just below the ground or water surface, were mostly detected and identified via particulate radionuclide monitoring. Under a CTBT one has to assume that a potential violator would try to avoid detection. Under such evasive scenarios the most difficult radionuclides to contain are the noble gases as they don't stick to crack surfaces or react with any other materials available. Based on characteristic radiation

and half-life there are four xenon isotopes that are most suitable for verification: ^{131m}Xe, ^{133m}Xe, ^{133}Xe and ^{135}Xe. Therefore, one of the technologies to verify the Treaty is the global environmental monitoring of these noble gases, as discussed in 3.3.

If an event detected by one of the stations of the IMS (or by national technical means) raises concerns about compliance with the basic obligations of the CTBT, an On Site Inspection (OSI) may be conducted to clarify whether a nuclear explosion has taken place or not. Such an inspection could take place only after entry into force of the Treaty, and would require agreement by at least 30 of the 51 members of the CTBTO's Executive Council. An inspection area of up to 1000 square kilometres would be searched by a team of inspectors. The purpose of an OSI would be to clarify whether a nuclear explosion has been carried out in violation of the Treaty and to gather any information which might assist in identifying the potential violator. The noble gases measured during an OSI are ^{37}Ar and radioxenons, as described in 3.1. and 3.3.

5.3. Fissile Material Cut-off Treaty

A Fissile Material Cut-off Treaty (FMCT) would strengthen nuclear non-proliferation by adding a binding international commitment to existing constraints on nuclear weapons-usable fissile material. It is proposed to negotiate such a treaty at the Geneva based Conference on Disarmament (CD), which would ban the production of fissile material for nuclear weapons or other nuclear explosive devices. It would not apply to plutonium and HEU for non-explosive purposes. It would also not apply to non-fissile materials, like tritium, and it would not address existing stockpiles.

Monitoring ^{85}Kr would be together with remote sensing methods a plausible verification technique for this possible FMCT [45].

6. Discussion and outlook

Techniques are available to measure the relevant noble gas isotopes ^{37}Ar, ^{85}Kr, ^{131m}Xe, ^{133}Xe, ^{133m}Xe, and ^{135}Xe in laboratories at ultra-low level. For each of these isotopes mobile sampling and measurement equipment has recently been developed. Currently the use of mobile equipment is studied and tested for the use of an onsite inspection under the CTBT, but other applications are also possible. At present there is no mobile measurement technique available that measures all noble gas elements simultaneously; however, the collection and analysis of argon, xenon

and krypton does have several things in common. Therefore we may see in the future a measurement system that is capable to perform these measurements together.

The worldwide background for ^{37}Ar and ^{85}Kr is well defined. The background of radioxenon, however, is not known accurately due to its regional variation. It is still complicated to distinguish globally a legitimate radioxenon release from a nuclear plant with the signal from a possible nuclear explosion. It depends from the source strength, the position of the station, the local background and the detection capability (MDC) of the measurement system used. A key issue in nuclear explosion monitoring need to be solved: we have theoretically modelled the presence of radioxenon in the world but the global background has not been verified with the measurements. This makes the distinction between civil sources of radioxenon and a nuclear test difficult in many areas. Therefore, more background measurements have to be performed in regions where there are nuclear facilities but no radioactive noble gas data are available yet (e.g. South Africa, South Asia and Persian Gulf region) to understand the absolute activity concentrations and the isotopic ratio at different places worldwide.

Technically, all global and national nuclear verification networks could be joined together to learn global backgrounds and to perform verification. The use of the existing IMS radionuclide network for other verification regimes like e.g. the WAES, seems to be obvious from a financial and scientific point of view. However, there are still political obstacles that do not allow different verification regimes to co-operate with full strength. The scientific community, however, can and should learn a lot from each other, in order to improve each system the best possible way, to make the world a better place to live...

7. Acknowledgements

8. Disclaimer

The views expressed in this publication are those of the author and do not necessarily reflect the views of the Comprehensive Nuclear-Test-Ban Treaty Organisation Preparatory Commission.

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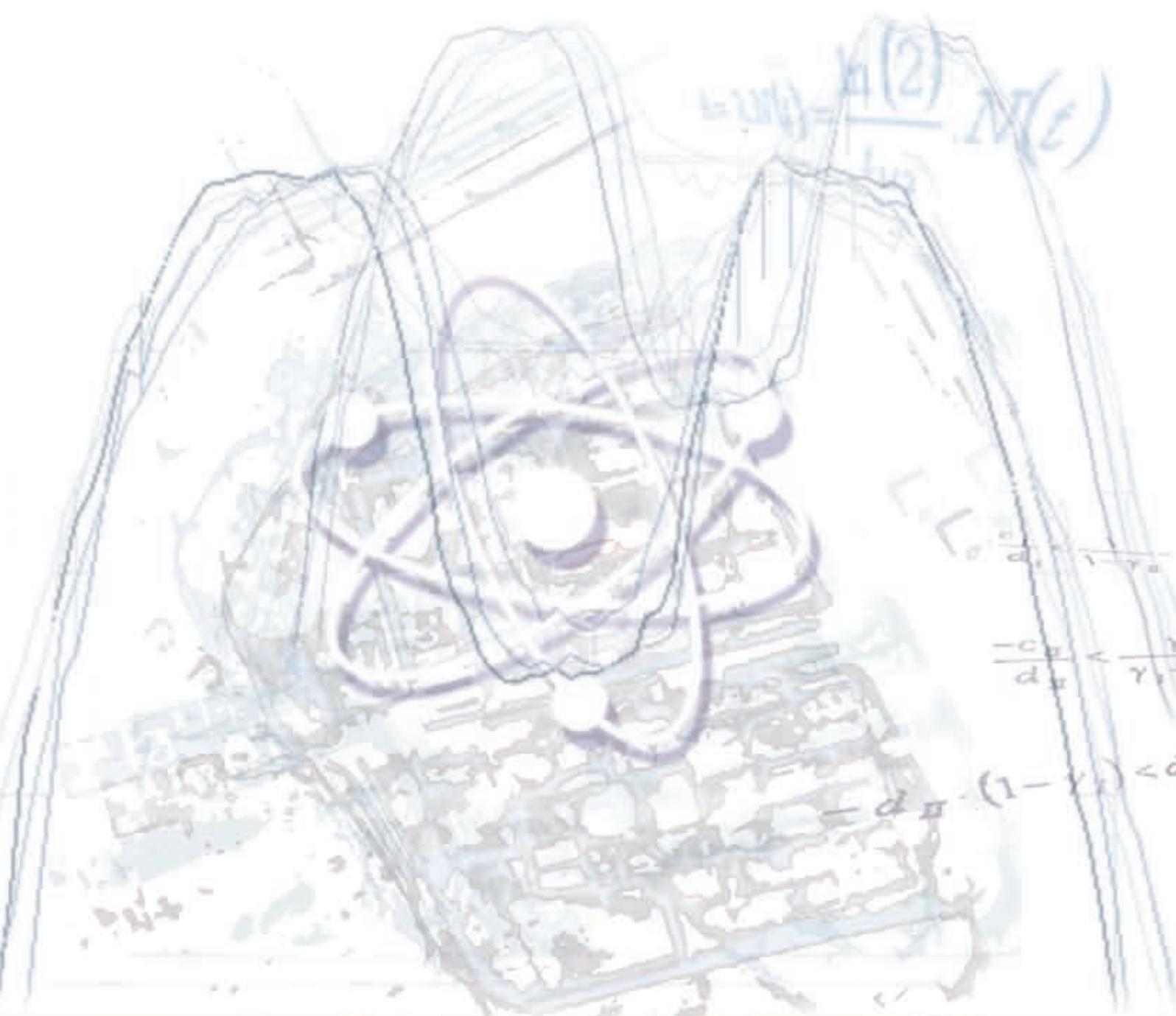## All ESARDA Bulletin issues are available from the ESARDA Secretariat
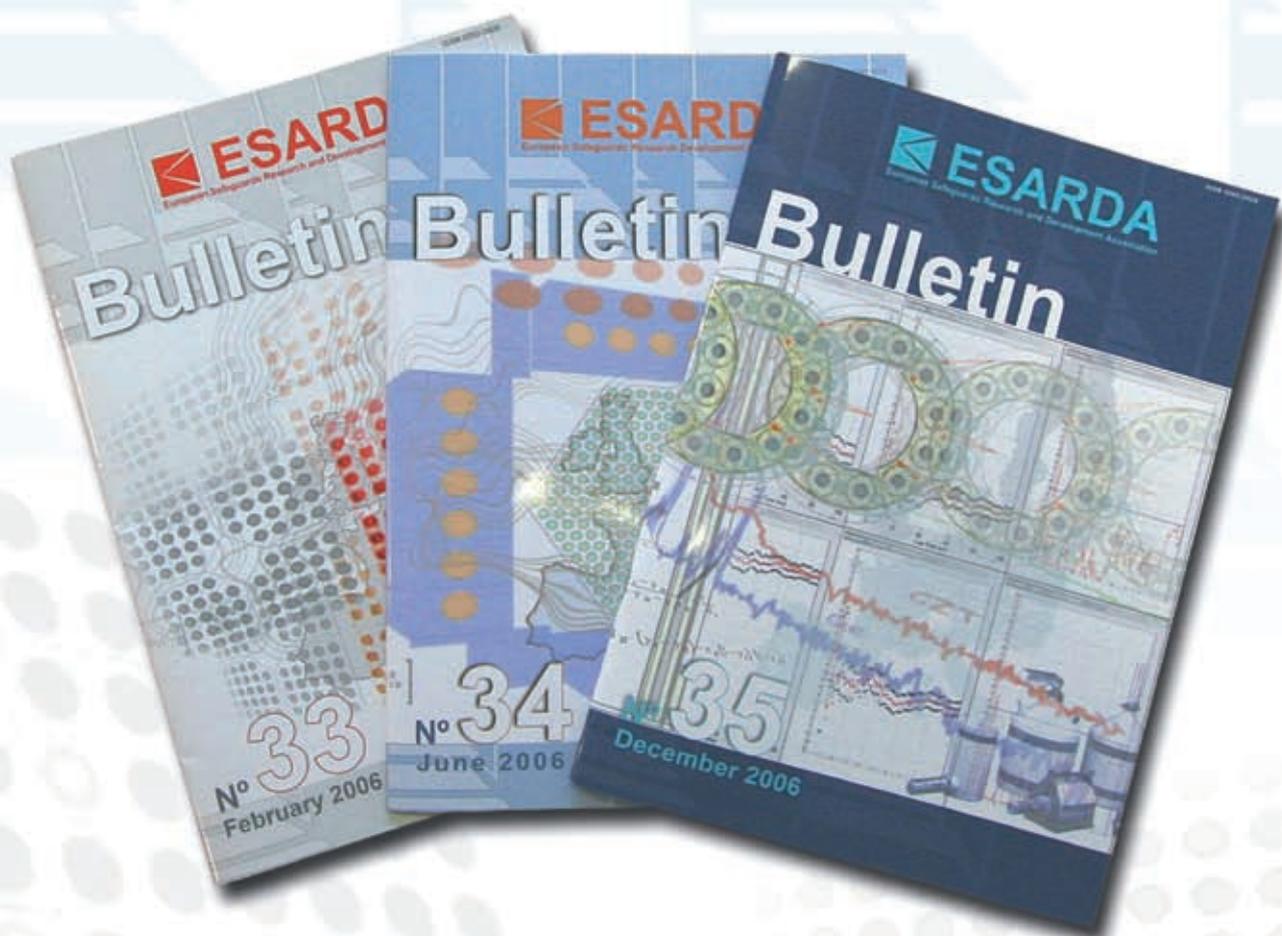
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