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BOOK SERIES

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ESARDA Course Syllabus

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Introduction

The European Safeguards Research and Development Association (ESARDA) has setup an academic course module with a full five-days program of lectures by experts in the field of nuclear safeguards and non-proliferation, visits to safeguards laboratories and some classroom exercises. This course is since 2004 annually organized by the Nuclear Security unit of the Joint Research Centre (JRC) in Ispra and meanwhile recognised as optional course in the European curriculum for Nuclear Engineering with three credits in the European Credit Transfer System (ECTS).

The course addresses the various aspects of a global nuclear non-proliferation system and explains how this system works in practice. It starts from the legal basis of the Treaty on Non-Proliferation of Nuclear Weapons at international scale and the EURATOM Treaty at regional scale, on the one hand and the technical aspects of the Nuclear Fuel Cycle on the other hand. After having explained the terminology and specification of nuclear materials as subject, the Safeguards Principles are defined, including the statistical aspects of accountancy and auditing. Then the nuclear safeguards technology is described with destructive and non-destructive nuclear material measurements, monitoring of transported or processed bulk material, containment and surveillance techniques. Their application in field is illustrated with a direct reporting of on-site inspections by the EURATOM and IAEA inspectorate. In the course, also innovative technologies as used for the Additional Protocol, environmental sampling and satellite imagery, are discussed and an excursion on nuclear forensics is given. An overview is given on the management and analysis of information, such as collected from open sources. Also analysis on import/export and strategic trade controls ares addressed. To comply with the ambition of an up-to-date course, the standard safeguards aspects are completed in the course with some topical lectures. Because of their temporary nature these are not included in the standard safeguards information package the syllabus aims to provide. Those topical lectures and case studies, such as on Iraq, Nuclear Security, Illicit Trafficking, or on the industry impact with the example of a Central Fuel Bank, serve as illustration for the discussed nuclear safeguards and non-proliferation issues. In a summary, the course deals specifically with technical aspects and application of safeguards and non-proliferation tools, including examples of in-field implementation of the safeguards principles and methodology at the different nuclear facilities.

This compact course is open to Master Degree students, in particular Nuclear Engineering students, but also International Relations/ Law Students and to young professionals. It aims also to provide understanding and communication of both very complementary aspects: technical and juridical/political.

Due to its success, the course was reached-out over several worldwide regions such as Asia and Africa, thanks to the financial support of EC DG INTPA. In Africa, two regional courses based on ESARDA course were successfully organized in 2018, the first in Pretoria for South African countries (13 countries) in February 2018 and a second in Algiers for north African and Sahel countries (9 countries) in October 2018. In South East Asia, two regional courses were organized for South East Asian countries, the first in Bangkok (Thailand) in June 2013 and the second in Kuala Lumpur (Malaysia) in November 2015. A third course in Asia was orgnised in September 2017 for China and took place at Tsinghua University in Beijing with about 80 participants from 18 Chinese universities and six private companies. The outreach ESARDA course constituted an important evolution with respect to classical ESARDA course, which is organized in JRC Ispra (Italy). Another important evolution of the course is initiated from the Coronavirus pandemic context, in fact the annual ESARDA course is successfully organised on-line since 2021 with an outstanding participation of African countries.

Last but not least, based on the success of this one week course and the high international interest it enjoys, an additional initiative was started, building upon this course and relying strongly also upon the involved experts, from ESARDA and partnering organisations, to implement a full academic specialised master programme in nuclear safeguards (60 ECTS points), where the first batch of 24 students graduated in November 2022 at the Politecnico di Milano under coordination by the European Nuclear Educational Network and funding by the European Commission.

Foreword

The continued interest in the deployment of nuclear technology for energy production, medical and other applications, urges the parallel development of the necessary human resources potential. Expanding this sophisticated nuclear sector with the same high-level standard of safety, safeguards and security requires highly skilled staff for design, operations, licensing, inspections ... Today fewer comprehensive, high-quality nuclear technology educational programs are observed than before in most countries and the ability of universities to attract students, to meet future staffing requirements of the nuclear industry is becoming seriously compromised. Thus, education and training in nuclear engineering and sciences is one of the cornerstones for the nuclear sector. Teaching in the nuclear field still seems strongly influenced by national history but it is time to strengthen resources and collaborate. Moreover, with the current nuclear security threats it becomes primordial that nuclear technology experts master the basic principles not only of safety, but also of nuclear safeguards, non-proliferation and security. The classic nuclear engineering courses cover well reactor operation and nuclear safety and security aspects, but are shortcoming with regard to technical aspects of non-proliferation, safeguards, import-export control etc.

This shortcoming on education in nuclear safeguards and non-proliferation was discussed by the ESARDA and it was decided to provide a continuum of didactical information, from a glossary that explains shortly the various concepts and objects used in nuclear safeguards, to a specialised course entirely devoted to teaching nuclear safeguards and non-proliferation concepts, methods and techniques. Both glossary and technical sheet examples can be found on the ESARDA website and the course activity is ongoing with annual safeguards courses. The course modules initiated in September 2002, thanks to the effective support of the ESARDA Secretary with an evaluation of the demand and interest for these Course Modules. This led to the setup of a task group in May 2003, which took shape as a new ESARDA WG, called the Training and

Knowledge Management Working Group – TKMWG. Since then, together with the JRC in Ispra a nuclear safeguards and non-proliferation course is organized every spring and is receiving international response of lecturers and students. This course is detailed on https://esarda.jrc.ec.europa.eu/course_en with schedule and abstracts for each lecture. The course program addresses:

i. "what is safeguarded" (definition of nuclear material subject to safeguards),

ii. "where is such nuclear material found" (nuclear fuel cycle),

iii. "which legal protective means" (the international and regional treaties, institutions and organisations),

iv. "how to control the nuclear material inventory and to audit a nuclear material accounting" (the techniques and methodology of verification, statistics for accounting & control),

v. "practical implementation of control measures" (how inspections are performed, and which tools the inspector has),

vi. "What additional information offers" (importance of the collection of open source data, illustrated with some case studies, and import/export and strategic trade controls).

The standard set of lectures, which represent about two third of the course, are given by representatives from regulatory bodies and inspectorates such as EURATOM, IAEA, IRSN, industry such as ORANO, and research organisations (Stockholm University, Hamburg University, JRC-Ispra/Karlsruhe/Geel). The course covers most of the safeguards and non-proliferation topics from the historical, legal and technical aspects such as:

- History of Non-Proliferation
- EURATOM, Historical Facts Material and Facilities subject to Safeguards
- Non-Proliferation Treaty
- Nuclear Fuel Cycle
- Nuclear Material Accounting and Control (NMAC)
- State System for Accounting for and control of Nuclear Material (SSAC)
- Safeguards On-Site Inspections
- Destructive and Non-Destructive Assay of nuclear material (DA and NDA)
- Containment and Surveillance
- Statistical Accounting State System for Accounting for and control of Nuclear Material (SSAC),
- Aspects of Export Control of Dual Use Commodities
- Information Collection and Analysis
- State Level Concepts and Approaches

The remaining part is completed with topical lectures addressing illicit trafficking, the Iraq case study, satellite imagery interpretation etc. With this structure of a stable core part and a variable set of invited lectures, the course is both sustainable and up-to-date.

A syllabus with background information on the basic principles for nuclear safeguards and non-proliferation was realized with the input of the lecturers and the reviewing effort of the different ESARDA Working Groups and covers the core part of the course. The objective of the course and the syllabus is to provide a homogeneous set of information material in nuclear safeguards and non-proliferation at the European and international level. It serves in particular as a reference work of didactical material reviewed by the ESARDA safeguards experts. This ESARDA-labelled course material should provide not only students but also teachers the basis for addressing nuclear safeguards and non-proliferation in their courses.

In this way, the ESARDA WG TKM aims to contribute to a two-fold scientific-technical and political-juridical education and training. This allows education of safeguards professionals with an equilibrated background in nuclear technology and in nuclear law, which are able to understand both, the language of lawyers and of nuclear technicians-scientists. In the EU, to our knowledge no multidisciplinary education initiatives in safeguards, non-proliferation exist. To streamline the educational resources, new synergies with interuniversity collaboration in a first step and interfaculty collaboration in a second step are fostered.

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Nuclear Non-Proliferation – A Brief Historical Background

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Introduction

The ultimate goal of nuclear non-proliferation is to prevent the spread of nuclear weapons. Ever since 1945, when the first atomic bombs were dropped over Japan, states, regional organizations, and international organizations have sought, by various means, to limit the possibilities of nations developing nuclear capacity. These efforts have resulted in the setting up of an international system of cooperation among countries; treaties and conventions have been signed and ratified, and global and regional organizations and national authorities have been established with the aim of stopping the illegal flow of nuclear materials and components. The system is far from perfect, and it isn't one that all the states of the world adhere to. In 1945, there was one nuclear power in the world – the United States. Today, there are nine states with nuclear weapon capacity – the United States, Russia, Great Britain, France, China, India, Pakistan, Israel, and North Korea. Against this backdrop, is it then really relevant to speak of success in the prevention of proliferation of nuclear weapons? The answer to that question depends on how the word "successful" is defined and on what are considered as attainable objectives. An optimistic person would surely say that it could have been a lot worse. Considering that a large number of states were contemplating acquiring nuclear weapons during the 1950s and 1960s, the current number of nuclear weapons states could have been much higher unless the work against nuclear proliferation had been successful. The optimist might add that there hasn't been a nuclear war since August 1945. On top of that, the optimist would possibly also point out that states such as South Africa, Ukraine, and Kazakhstan have voluntarily relinquished their nuclear arsenals. All in all, in the eyes of the optimist, the system of nuclear non-proliferation has functioned well, despite certain deficiencies and shortcomings.

On the other hand, a pessimist would probably claim that all the efforts to create a non-proliferation system have hardly succeeded in making the world a safer place; if anything, the opposite is true. The pessimist would also most likely assert that the current multipolar international system is much more insecure and less predictable compared with the bipolar system during the cold war. During the cold war, the world was divided into two power blocks, and the two superpowers, the United States and the Soviet Union, were able to control each other, thereby reducing the risks of a nuclear war. Today, however, we have several countries with nuclear weapons capability. As a consequence, the prospects for major crises have increased dramatically and a future nuclear war cannot be ruled out as unthinkable.[1] To this, the pessimist would surely add the threat from terrorist groups, which, according to some experts, have tried to acquire nuclear weapons. Who is right, the optimist or the pessimist? Once again, that depends on the vantage point and what is considered to be the ultimate attainable objective in efforts to create a safer world.

Since 1945 three main approaches have been used to reduce the number of nuclear weapons: disarmament, arms control and non-proliferation. These three approaches, or endeavours, have meant different things for various actors over time. For example, during the 1960s the United States and the Soviet Union often used the term disarmament in conjunction with initiatives to create agreements to promote international security.

[1] About the prospects for major crises and military conflicts in a multipolar system, see for example, John F. Mearsheimer, Back to the Future: Instability in Europe after the Cold War. International Security, Summer 1990 (Vol. 15, No. 1).

However, the intention was never to aspire to a complete abolishment of all nuclear weapons. Disarmament in the eyes of the US and Soviet state leaders meant, in real terms, arms control or non-proliferation. The two superpowers overarching aim was to implement an international order that allowed them to keep their own nuclear weapons while preventing other states from acquiring those weapons.

To understand where the world community stands today in the efforts to create a safer world without nuclear weapons, we need to come to grips with how the major actors (primarily the United States and the Soviet Union/Russia) have interpreted and used these three terms during different periods since 1945. By doing this we can better understand the intentions behind radical proposals to reduce or abolish nuclear weapons and how they have been handled at international settings since the cold war period.

In this chapter, the three main approaches are used according to the following definitions:

- Nuclear disarmament: endeavours that aim to abolish nuclear weapons completely.
- Nuclear non-proliferation: legal and/or political undertakings with the aim of limiting the spread of nuclear weapons.
- Arms control: efforts to reduce the development, stockpiling, production, proliferation and usage of nuclear weapons through political and/or legal commitments.[2]

Background: 1939-45

When was the first step taken towards what was later to be called nuclear energy and its use? It is impossible to cite an exact date or to point to a single, decisive discovery. The idea that the things we can see with the naked eye consist, in their turn, of smaller elements has more or less been taken as a fact in the discussions of learned philosophers since time immemorial. Already during antiquity, Democritos speculated that the smallest elements of matter consisted of what he called "atoms." In the 17th and 18th centuries, Enlightenment philosophers developed atomic models describing the structure of the world. For example, Isaac Newton imagined something resembling miniature billiard balls which he believed formed the basis of the mechanics of the universe. But there have also been scientists in modern times who have doubted the existence of the atom. The world-famous German physicist Max Planck even believed that the atom could be considered a British invention, and if such an element of matter existed, he asserted, it could not be mechanical in nature. A mechanistic atom, Planck writes in his doctoral dissertation of 1879, is inconsistent with the second law of thermodynamics.[3]

However, the first evidence that there exist small particles, atoms, in nature was found during an experiment conducted by the physicist Ernest Rutherford in 1911. Rutherford was inspired by the research on radioactivity conducted by Henri Becquerel and Pierre and Marie Curie in Paris.[4] During the 1920s and 1930s, the frontlines of research were being moved forward at dizzying speed, and both physicists and chemists took part in this accelerating scientific development. Indeed, it is probably impossible to establish an exact date. However, if one still wants to attempt finding a date, especially one that signalled a decisive breakthrough for the direct civilian and military use of nuclear energy, then January 6, 1939 would not be a bad choice. For it was on this day that the German physicists Otto Hahn and Fritz Strassman described, in the journal *Naturwissenschaften*, their discovery of a new type of nuclear reaction – fission. In an experiment, they had bombarded a uranium atom and successfully split it into two lighter elements. Other researchers became

[2] Barry Kolodkin, "What is arms control?"18 March 2017,https://www.thoughtco.com/what-is-arms-control-3310297
[3] Richard Rhodes, The Making of the Atomic Bomb. Touchstone Books, New York 1986, p. 30.
[4] Ibid., p. 42.

inspired. Soon thereafter, the Austrians Lise Meitner and Otto Frisch demonstrated experimentally that this fission released energy, an energy that it would be possible to exploit. A couple of weeks after that the Hungarian physicist Leo Szilard was able to establish that two neutrons are released when a neutron that has already been released in the process collides with another (^{235}U) atom.[5] All those discoveries had an enormous impact on the ongoing physics research all over the world. Now it seemed that the energy issue had been solved for all time.

Unfortunately, it was not the civilian use of nuclear energy that became the first tangible application of this new science. During the Second World War, a race emerged between Nazi Germany and the United States to use this new science to produce nuclear weapons. Leading scientists were engaged in this competition. For example, Albert Einstein, at the request of Leo Szilard among others, wrote a letter to the US President Franklin Roosevelt in August 1939 that became the launching pad for the program to manufacture atomic bombs. In the letter, the famous physicist explained that Germany had begun experiments aimed at producing highly enriched uranium for the development of nuclear weapons. Einstein advised Roosevelt to commit resources to developing nuclear weapons before Nazi Germany would be able to succeed in doing so.[6] However, it took a long time for Roosevelt and the US administration to give green light to the plans that Einstein expressed in his letter. A project to develop atomic bombs was a major commitment and would require huge financial and scientific resources. Decision makers and advisors within the American administration wondered if it really would be wise to invest all needed scientific skills and capital in a project whose results were difficult to overlook. In October 1941, however, President Roosevelt made the decision to launch the world's largest military industrial project to date, namely the Manhattan Project.

Roosevelt´s approval to go ahead with the project had been preceded by a convincing research report that affected the outcome of the decision. During the spring of 1941, the top secret British so-called MAUD Committee's findings had been handed over to the United States. The MAUD committee, whose members represented a network of physicists from outstanding British universities, had in two reports summarized its conclusions on how a production of nuclear weapons could be carried out. Despite the excellent nuclear research conducted in United Kingdom, the country was far from able to allocate needed resources to realize such a huge and complex project. The fierce war with Nazi Germany devoured the country´s all capital and manpower.[7]

The Manhattan project has often been characterized as the first model of how large-scale research can be created – so called "big science". Before WWII, universities and research institutes had in general scarce resources and were not in a position to build larger research environments. However, the necessities of war forced governments in most nations to allocate financial resources to build large-scale research projects with the goal to develop efficient weapon systems. As a consequence, large and costly scientific and technical cooperation projects emerged among universities, research institutes and companies in most countries affected by the war. The Manhattan project was such a “big science” project, but on a mega scale. At most, more than 130,000 people were involved in the efforts to develop nuclear weapons! Cadres of scientists, engineers, civil servants, workers were employed during the war years. A dynamic and authoritarian general, Leslie Groves, became the director of the Manhattan project in 1942 and he ran the project with an iron fist.

[5] David Fischer, History of the International Atomic Energy Agency: The First Forty Years. IAEA, Vienna 1997, p. 15. et passim.
[6] Rhodes, p. 303-314.
[7] David Holloway, Stalin and the Bomb. The Soviet Union and the Atomic Energy, 1939-1956. Yale University Press, New Haven & London, 1994, pp. 79-82.

The nuclear physicist Robert Oppenheim was connected to the Manhattan project as a scientific leader and in this capacity he is often referred to as "the father of the atomic bomb".[8]

The Great Race: Who will have nuclear weapons first?

The overarching objective of the British-US policy regarding Nazi Germany became to prevent the enemy state to get access to uranium. Access to uranium constitutes the key precondition to initiate a nuclear weapon program. During the Second World War the knowledge regarding the world´s uranium resources was quite limited. At that time, the main source of uranium was Belgian Congo, and British-US intelligence knew that Nazi Germany had received a stock of uranium from that origin. In 1944 it became obvious in US and British intelligence circles, however, that Nazi Germany would hardly be able to produce nuclear weapons during the ongoing war. The German bomb project had not advanced as far as American and British experts had expected it to do a couple of years earlier. Besides Germany, also the Soviet Union was considered as a potential threat in the long run. Although U.S.A and British experts drew the conclusion that it was likely to assume that some theoretical studies in the nuclear field had already been initiated, they would hardly succeed to start a nuclear program in good many years. General Groves claimed that it would take at least 20 years for the Russians to develop their own nuclear weapons. In fact, the leading Soviet nuclear physicist Igor Kurchatov had already in 1939 informed his government and its leader, Joseph Stalin, about the prospects of exploiting the fission energy for military purposes.[9] Some laboratory experiments were also conducted in Soviet launched the following year. The German invasion in 1941 and lack of uranium, however, hampered the Soviet nuclear research. It was not until the end of the war that the Soviet exploration started seriously. At that point, the Soviet geologists had found rich uranium resources, mainly in Central Asia and in Estonia, which could be used in the nuclear weapons program that was launched after the war. [10]

In June 1944, the United States and Great Britain signed an agreement, the Combined Development Trust, with the goal of winning control over the world's reserves of uranium. The most important goal was to gain influence over the world's major uranium deposit in the Belgian Congo, and this was achieved in 1944-45 when a secret agreement was entered into force with the Belgian government-in-exile concerning the commercial exploitation of the country's uranium reserves. This efficient uranium cooperation thus resulted in the United States and Great Britain controlling more than 97 percent of the world's uranium production.[11]

On August 6, 1945, the first nuclear weapon was dropped over Japan. It was a uranium bomb named "Little Boy" which detonated over Hiroshima and which by year's end had extinguished some 140,000 human lives. Five years later, the number of deaths caused directly by "Little Boy" had risen to 200,000. The population of Hiroshima at this time was around 400,000.[12] These numbers indicate the explosive force of the world's first nuclear device.[13] Three days later, on August 9, the second bomb was dropped on Japan. This time, it was a plutonium bomb, and the name of the city where it was dropped was Nagasaki. In December 1945, 70,000

[8] About Robert Oppenheimer, see Kai Bird and Martin J. Sherwin, *American Prometheus: the triumph and tragedy of J. Robert Oppenheimer*, Atlantic Books, London, 2008.

[9] Rhodes The making of the Atomic Bomb, p. 500 et passim. On Igor Kurchatov and his activities, see Paul R. Josephson, Red Atom: Russia's Nuclear Power Program from Stalin to Today (New York: W.H. Freeman; Basingstoke: Macmillan, 1999), p. 11 et passim.

[10] On uranium production in Estonia, see Ello Maremäe, Hain Tankler, Henno Putnik, Ige Maalmann, Historical Survey of Nuclear Non-Proliferation in Estonia, 1946-1995, Kirguskeskus, December 2003; Thomas Jonter & Lars Van Dassen, "Making Historical Surveys of States' Nuclear Ambitions: Experiences from the Baltic Sea Region," The Nonproliferation Review, March 2005, vol. 12, No. 1.

[11] Holloway, p. 174.

[12] Richard Rhodes, The Making of the Atomic Bomb, p. 733 et passim.

[13] On the explosive force, see Rhodes, p. 561, 643.

people had died in Nagasaki, and after another five years the number had increased to 140,000.[14] It was immediately obvious that a weapon with a monstrous explosive force had been produced. Now, the chief concern was preventing this monstrous weapon from spreading.

The Failure of Anglo-American Nuclear Weapons Monopoly: The Period of 1945-1952

On April 25, 1945, more than three months before the two nuclear bombs were dropped over Japan, the U.S. secretary of war, Henry Stimson, reported to President Truman that the control of nuclear weapons "*will undoubtedly be a matter of the greatest difficulty and would involve such thoroughgoing rights of inspection and internal controls as we have never heretofore contemplated.*"[15]

The three states that signed the Quebec treaty, and which together controlled the production of uranium and thorium during the war, also took the first step towards finding a global solution to the problem. In November 1945, the United States, United Kingdom and Canada presented a common strategy when they announced the Three Nation Agreed Declaration on Atomic Energy, which said that the newly formed supranational United Nations organization should be given responsibility for handling the surveillance and control of the global use of nuclear energy in order to promote its peaceful use exclusively. Shortly thereafter, at a meeting in Moscow, the United States and United Kingdom proposed the establishment of a new authority, the United Nations Atomic Energy Commission (UNAEC), in line with the Three Nation Agreed Declaration on Atomic Energy. The Soviet Union accepted the proposal but maintained that the work of the UNAEC should be controlled by the Security Council with its built-in veto mechanism, something which the Americans and British agreed to. In January 1946 the UNAEC was formed, and in the subsequent years various ideas were put forward about how to abolish nuclear weapons and control the peaceful use of nuclear energy. These were often radical proposals, which were soon crushed by the cold war manoeuvrings of the superpowers.[16]

One example of a proposal that ended up in the dustbin is the so-called Baruch Plan of June 1946. The objective of this proposal was to create an organization, the International Atomic Development Authority (IADA), which would either have the right of disposition or exercise control over all nuclear energy activities in the world that were considered a threat to global security. One of its first tasks would be to gather and maintain complete and exact information about the world's reserves of uranium and thorium and to take control over them. The Baruch Plan was aimed at creating an international organization with real powers which would handle transactions involving nuclear materials. According to the proposal, the IADA would also have authority to impose sanctions on nations that did not adhere to the international regulations, and no nation would have the right to veto its decisions.

The Soviet Union under Stalin's leadership did not accept this proposal. In Stalin's view the abrogation of the veto right was an impossible proposition since this was one of the most important principles of the system which the four Allied powers of World War II had agreed upon. According to the Soviet view, these states alone – France, the Soviet Union, Great Britain, and the United States – should uphold the world order. Moreover, the Russians had already decided to acquire nuclear weapons of their own. The Baruch Plan would have rendered a Soviet nuclear weapons program impossible. On the American side many were also sceptical

[14] Rhodes, p. 740 et passim.
[15] Fischer, p. 18.
[16] Fischer, ibid.

about the realism of the Baruch Plan. Six days later, the Soviet foreign minister, Andrei Gromyko, put forward a counterproposal that contained a reversed action plan. The Soviet proposal turned the logic of Baruch's basic idea of "control first, then disarmament" on its head, and claimed that it would be better to start by destroying all nuclear weapons (no later than three months after an international convention had come into force), and then to have the UNAEC turn to IADA which would verify that the treaty was observed.

One year later, the Soviets proposed the creation of an organization similar to the system of reporting and inspections that was set up 20 years later through the Non-proliferation Treaty of Nuclear Weapons (NPT). However, there was one important difference compared with the NPT: in the Russian proposal it was the nuclear energy activities of the United States and the Soviet Union that would be subject to control. The United States and its allies found the proposal insufficient and rejected it. On the whole, the discussions in the UNAEC were unsuccessful. Already at the end of 1949, after 200 sessions, the UNAEC was abolished.[17]

In September of that year, the Soviet Union performed its first nuclear test. The announcement came as a shock to US officials since American experts had assumed that it would take the Soviet Union at least 20 years to become the world's second nuclear power.[18] The Cold War was now a fact, and the efforts directed at creating a globally accepted nuclear materials control system that would enjoy the support of both superpowers were from now on and for a long time thereafter regarded as utterly naive.

At the same time as discussions were going on about the setting up of a global control system for nuclear energy, the United States government took measures, based purely on its perceived national interests, aimed at limiting other states' access to nuclear materials and other products which might be used for nuclear weapons production. The overarching nuclear energy policy of the United States throughout the Cold War can be summarized as consisting of the following objectives:

1. To increase the military strength of the United States by maximizing, through various forms of cooperation, US nuclear weapons interests, while simultaneously thwarting other countries' attempts to acquire nuclear weapons of mass destruction.
2. To prevent the proliferation of nuclear weapons.
3. To control the sale of nuclear materials and other equipment that might be used for nuclear weapons production.
4. To make other countries dependent on the United States in the nuclear energy area. By creating this dependence, the United States would be in a position to control other countries' development of nuclear energy.[19]

In 1946, the US Congress passed the first law dealing with the use of nuclear energy in the United States, the so-called McMahon bill. In accordance with this law, the United States Atomic Energy Commission (AEC) was created, with the objective of verifying that the new law was observed in the United States and of maintaining oversight of American trade in nuclear materials and technology. The main purpose of the US legislation was to stop the export of strategically important nuclear materials and products to other states. Some exports would be allowed, however, if they were perceived to further American scientific and military interests.

[17] Ibid., p. 19 et passim.
[18] Ibid., p. 21.
[19] Gunnar Skogmar, Atompolitik: sambandet mellan militärt och civilt utnyttjande av atomenergin i amerikansk utrikespolitik 1945-73. Lund 1979.

In October 1952, United Kingdom became the world's third nuclear power. There was a substantial fear within the US administration that more states would soon be able to achieve nuclear weapons capability since both information about the production technique and nuclear materials were spreading. Furthermore, various reports described the rapid growth of the Soviet nuclear arsenal. For example, the official U.S. Candor Report of 1952 states that the Soviet Union may shortly have the capacity to obliterate 100 of the key U.S. industries and thus win the third world war.[20] Since both the Soviet Union and United Kingdom had succeeded to achieve nuclear weapons, it was obvious that the United States strategy to create a monopoly of the world´s uranium had now failed.

To summarize the period 1945-52, it´s fair to say that disarmament dominated the international efforts to get rid of all nuclear weapons. Disarmament in this context meant endeavours to abolish nuclear weapons completely. The proposals that were presented and discussed within the UNAEC framework were based on that notion. It became obvious, though, that the US ambition to create a nuclear monopoly had failed since both the Soviet Union and Great Britain succeeded in acquiring nuclear weapons during up until the end of 1952.

The Creation of the International Atomic Energy Agency: 1953-1957

Against the background that the monopoly strategy of United States had failed, the new president, Dwight D. Eisenhower, launched a new policy, the so called "Atoms for Peace" program. In December 1953, Eisenhower gave a speech in the UN where this new policy was explained with the goal to foster a global cooperation in the nuclear field. United States should no longer prevent other countries from developing their nuclear energy capability. The basic idea was that the nuclear powers would cooperate and set up a common nuclear energy pool of nuclear materials and technology which other states would be able to use to develop civilian nuclear energy. The first step had now been taken towards creating a globally comprehensive control of nuclear energy. Eisenhower's policy was aimed at achieving a broader cooperation with regard to research and development of nuclear power. From now on, transfer of nuclear material to other countries was allowed – also in the form of highly enriched uranium and plutonium 239 – provided that the receiving country committed itself not to use the acquired nuclear material for nuclear weapons production.[21]

The "Atoms for Peace" program was a part of the cold war between the superpowers. To begin with, the Soviet Union was sceptical about the American plans. The Soviet foreign minister Molotov held that if Eisenhower's idea of establishing a global pool of fissile material were realized, there would be an increased risk of fissile material spreading since such a system was considered vulnerable and prone to manipulation. A new proposal was worked out in which the idea of a common safe-keeping bank that would own and control nuclear materials was abandoned in favour of a concept where the supranational organization would function as a clearing house for transactions involving nuclear materials. According to this proposal, then, the supranational authority would neither own nor manage the fissile material but instead act as a controller. In 1955, eight states began the task of producing a concrete treaty text for the international organization which three years later would be established as the International Atomic Energy Agency. This group of states consisted of the United States, Great Britain, France, Canada, Australia, Belgium, and later Portugal. The latter five states had been included since they were important producers of uranium at this time. Once this Eight Nation Negotiations Group had agreed upon a common treaty text, other nations would be invited to take

[20] Fischer, p. 22 et passim.
[21] Skogmar 1979, p. 74 et passim.

part. In the same year, the Soviet Union initiated negotiations concerning participation in the IAEA organization[22], something which would scarcely have been possible had Stalin still been in power (Stalin died in 1953).

In August 1955, an important conference was held in Geneva at which the guiding principles for this gigantic cooperation were established. It was the biggest scientific conference in the world up to then, with more than 1,500 participating delegates and more than 1,000 scientific papers presented. It was also the first time that large numbers of Soviet researchers had taken part in a scientific conference together with scientists from the West. The conference led to the abolition of secrecy in a number of areas. France went so far as to reveal the technology behind the reprocessing of used nuclear fuel to produce plutonium. After this conference, the only activities in the nuclear energy field that remained secret were the techniques for producing nuclear weapons and enriching uranium.[23]

In the fall of 1955, the United Nations General Assembly decided that the Eight Nation Group should be expanded into a group consisting of twelve nations. Third World nations such as Brazil and India were now also included in the group that would produce a workable treaty text for the IAEA. On February 27, 1956, this Twelve Nation Group presented a proposal for regulations that remains largely the same today in terms of both content and form. The text has two main purposes: (1): to promote global dissemination of civilian nuclear technology and know-how; and (2): to supervise and control this technology and know-how in order to prevent the proliferation of nuclear weapons (Article II). These two general purposes can in their turn be divided into five basic IAEA objectives which are formulated in the current articles:

- To promote research, development, and application of peaceful nuclear energy (Article III.A.1);
- To provide materials, service, equipment, and facilities for such research, development, and application of nuclear energy "with due consideration for the needs of the under-developed areas of the world" (Article III.A.2);
- To promote the exchange of scientific and technical information (Article III.A.3);
- To create and apply safeguards in order to ensure that no nuclear related assistance or assets associated with the IAEA are used for military purposes (Article III.A.5);
- To establish and develop nuclear safety standards (Article III.A.6).[24]

The work and objectives of the IAEA are both political and economic in nature, and it was therefore decided that the organization be put under the authority of the UN General Assembly. And since some of the IAEA's activities can have security policy consequences, it was decided that the Security Council would also receive reports concerning developments falling within its competence. This arrangement meant that the permanent members of the Security Council would be able to exercise their veto to block sanctions and other measures. It was precisely this state of affairs that the Baruch plan sought to avert, but the Soviet Union had refused to accept it.[25]

A so-called Board of Governors, with extensive executive powers, was formed, which meant that the UN General Assembly could only recommend certain proposals for measures to be taken. For practical purposes, the Board of Governors makes most of the decisions concerning safeguards: it designs and approves

[22] Fischer, p. 30 et passim.
[23] Skogmar 1979, p. 79.
[24] Ibid., p. 35 et passim.
[25] Ibid., p. 36.

safeguards systems, appoints inspectors, and approves safeguards agreements. The Board of Governors is also the authority that determines whether a state is living up to its agreed-upon obligations regarding safeguards.[26] In cases where states do not fulfil their obligations, the Board of Governors reports to the Security Council and the General Assembly – something which happened in the aftermath of the Persian Gulf War of 1991, when Iraq was judged to have breached the safeguards agreement that existed between the Iraqi government and the IAEA.

How is this important authority organized? As with most matters involving international cooperation, it is a question of politics, with the institutional make-up reflecting power, historical realities, and negotiating skills. Following a number of discussions in the Twelve Nation Group about the organization of such a body, during which different principles of participation were the subject of disputes, India put forward a proposal that won acceptance. In the proposal, which was also put into effect, the world was divided into eight regions: North America, Latin America, Western Europe, Eastern Europe, Africa and the Middle East, South Asia, Southeast Asia, the Pacific and the Far East. Independently of this geographic division, the five most advanced states in the field of nuclear energy technology (which also included the capacity to produce nuclear materials) were to form a group. Although they were never mentioned by name in the Indian proposal, it was obvious that the states in question were the United States, the Soviet Union, Great Britain, France, and Canada. Meanwhile, a second group of advanced nations would be designated according to the same criteria, but these states would be picked from the regions that were not represented in the first group of top nations. It was implied that Brazil would represent Latin America, India would represent South Asia, South Africa would represent Africa and the Middle East, Japan would represent the Far East, and Australia would represent South East Asia and the Pacific. Belgium, Portugal, Czechoslovakia, and Poland also became members of the organization because of the high level of uranium production in these countries. One representative seat would have responsibility for providing technical assistance, and this assignment went to the Nordic countries, with the seat rotating between Denmark, Finland, Norway, and Sweden. Since then, the membership of the Board of Governors has increased to 35 states, the top group has expanded from five to ten nations (including China), and the Middle East has merged with the South Asia region.

The crucial question was how the global safeguards system would be designed and how it would work in practice. Article II says that the organization's objective is to prevent the spread of nuclear weapons. But how would it be possible agree on a system that would take the divergent interests of the members states into consideration and at the same time be acceptable to the superpowers? The proposals that were worked out and became the subject of discussions and negotiations were patterned on the United States' bilateral cooperation agreements in the nuclear energy field, which were now being concluded on a wide front within the framework of the "Atoms for Peace" program.

The IAEA was formally established in the same year, 1957, as another important supranational organization, namely the EURATOM. The Treaty of Rome, which was to regulate the economic, political, and social affairs of a unified Europe, was also meant to deal with nuclear energy issues. It was felt that the European Community needed a common nuclear energy policy, and for this reason the EURATOM was formed. With US encouragement, the formulation of the inspection regulations in the Treaty of Rome became almost identical with the language in the IAEA Statutes. This is also true of the nuclear material control system of the OECD, which was managed by the European Nuclear Energy Agency (the Common European Safeguards System, see

[26] Ibid., p. 37.

section II, where Sweden's role in the EURATOM is described). The rights of inspection that the IAEA has pursuant to Article XII in the treaty text can be summarized in five points:

1. To inspect and approve the design of facilities where nuclear related activities take place (but only to verify that these are not used for military purposes);
2. To demand that operating records be kept (Article XII.A.3);
3. To demand and obtain reports (Article XII.A.3);
4. To approve the methods for reprocessing used fuel;

To dispatch inspectors to facilities with which the IAEA has safeguards agreements. The inspectors should in principle have access at any time to locations, data, and personnel connected with nuclear posts that are placed under safeguard.[27]

The inspectors are obliged to report any deviations committed by a state to the secretary general, who in turn is responsible for reporting to the Board of Governors. The latter body may, in case it is established that a state has not followed an existing treaty, demand that it fulfill its obligations. The Board of Governors can also report this non-observance of treaty obligations to the other member states, and to the Security Council and General Assembly. The IAEA has certain sanctions measures at its disposal (Article XII.C.), but in the end it is the Security Council that decides whether more far-reaching sanctions should be imposed, and, if so, how this should be done.[28]

After protracted negotiations, the Twelve Nation Group succeeded in producing a treaty text. But it wasn't until the 1970s, after the signing of the Non-proliferation Treaty, that the IAEA took over responsibility for safeguards on a wide front. One of the reasons why the IAEA did not take over responsibility for nuclear material control was that none of the proposed basic ideas about using the organization either as a common pool or control station for fissile material was ever realized. Another reason was that the Soviet Union and certain Third World countries, led by India, were against the idea of assigning this comprehensive responsibility to the IAEA.[29] A third reason lay in the actions of the United States at this time. According to the US, the IAEA did not yet have the required stability to manage a global surveillance and control system.

The cooperation treaties that were signed between the United States or the Soviet Union on the one hand, and various other states on the other hand, were bilateral, and security surveillance was a matter that was regulated and controlled by the two parties that had signed the agreement. The United States signed its first treaty, with Turkey, in 1955, and by 1959 Washington had signed cooperation treaties with 42 nations. In most cases, the treaties had a duration of five to ten years, and in some cases, 20-25 years. The Soviet Union began to compete with the United States in this regard, especially in the Third World, and by 1968, the Russians had cooperation treaties with 26 states.

Most of the treaties proposed by the US contained provisions concerning the possibility of replacing the arrangement for safeguarding the observance of the bilateral agreements with a system managed by the IAEA. The Soviet Union demanded neither bilateral nuclear material control nor that the IAEA be given

[27] Ibid., p. 43.
[28] Ibid.
[29] Ibid., p. 82.

responsibility for safeguards. Instead, the cooperating state had to promise to use the received aid for peaceful purposes only, and to return the used nuclear materials to the Soviet Union afterward.[30]

The successful strategy to prevent other states from acquiring atomic bombs meant in practice that the nuclear weapons states could both keep their nuclear weapons and increase their numbers drastically. In 1952 there were around 1000 nuclear weapons in the world and five years later the number had increased to 7000. In 1962, the same year as the Cuban missile crisis took place, this enormous arms race had resulted in a capacity of 30 000 nuclear weapons. Although the logic behind the nuclear arms race had to do with the strong faith in the deterrence theory, the super powers were nevertheless afraid that this dynamic process could lead to an uncontrollable situation where a nuclear war was not unthinkable. Consequently, a new dimension started to emerge between the two superpowers in the efforts to reduce the risks of a nuclear war: arms control. Even though all these negotiations between US and Soviet diplomats and military experts were all about arms control, the term that was used was disarmament. The term disarmament started to lose its original meaning to abolish nuclear weapons completely. Disarmament underwent a change to instead mean various efforts to create stability by entering into agreements on usage, stockpiling and proliferations of nuclear weapons. In practice, the nuclear arms race increased and no substantial agreements to prevent proliferation and stockpiling were signed. In parallel with these ongoing fruitless talks between the superpowers, grass root movements against the arms race started to grow internationally with the message that serious steps need to be taken toward real disarmament.[31]

The NPT is put into effect: The Period 1957-1990

The first five years in the history of the IAEA were filled with ideological discussions and lined with practical problems, even though much was done to develop competences and knowledge in order to live up to the stipulated objectives. However, during this initial period, the IAEA and its member states did not succeed in creating a comprehensive, efficient system for preventing the proliferation of nuclear weapons. During the 1950s and 1960s, a number of states were also contemplating acquiring nuclear weapons. Nations such as China, France. Sweden, Switzerland had extensive plans for producing nuclear weapons of their own. Against this background, President Kennedy asserted in the early 1960s that there was an obvious risk that by the mid-1970s there would be 10-20 nuclear states in the world if nothing were done to prevent this development.[32]

But, there were or course ideas on how to move forward in the efforts to prevent a spread of nuclear weapons and some progress was made. Ever since October 1958, Ireland had maintained that the UN General Assembly ought to agree on a treaty aimed at preventing the "wider dissemination of nuclear weapons." The proposal was never put to a vote at that time, but it inspired the subsequent work in the UN and the IAEA in the non-proliferation field, and thus it can also be regarded as the first, embryonic draft of what was to become the NPT in 1968. In December 1961, the UN General Assembly adopted a resolution which was based on an Irish proposal for initiating negotiations about a treaty aimed at preventing the spread of nuclear weapons. Negotiations got under way and various treaty texts were discussed, and finally a treaty was ready for nations to start signing. On February 14, 1967, the Latin American nations signed a non-proliferation

[30] Fischer, p. 29.
[31] A good overview of these grass root movements and their effects world wide, see Lawrence S. Wittner, Confronting the Bomb. A Short History of the World Nuclear Disarmament Movement. Stanford University Press, Stanford 2009.
[32] News Conference 52, Mach 21, 1963, https://www.jfklibrary.org/archives/other-resources/john-f-kennedy-press-conferences/news-conference-52

treaty – the Treaty of Tlatelolco, later known as the Treaty for the Prohibition of Nuclear Weapons in Latin America – which constituted an important step towards the achievement of the comprehensive treaty on non-proliferation that was signed the year after.[33] The Non-Proliferation Treaty came into force in 1970, and in 2018 has been ratified by 191 states. The NPT can be said to have three purposes:

1. To prevent the dissemination of nuclear weapons
2. To promote nuclear disarmament
3. To promote the peaceful use of nuclear energy

The treaty consists of eleven articles.[34] Article 1 prohibits nuclear states from transferring nuclear weapons and equipment that can be used for producing nuclear weapons to other parties. In addition, nuclear-weapons states are prohibited from helping, encouraging or inducing non-nuclear weapons states to develop nuclear-weapons capability. The NPT further prohibits, by Article 2, the group of non-nuclear states from receiving or trying to produce nuclear weapons or nuclear devices of their own. In accordance with Article 3, the latter group is also under the obligation to sign a safeguards agreement with the IAEA regulating the surveillance and control of nuclear materials in cases where the state in question handles nuclear materials and equipment covered by the IAEA's guidelines. The safeguards agreement gives the IAEA the right to verify that a state's possession of nuclear materials corresponds with the amount it has declared. Furthermore, all states that have signed and ratified a safeguards agreement have committed themselves not to transfer nuclear material or nuclear related technological equipment to states that do not have binding control agreements with the IAEA. Take Sweden for example. Sweden is a member of the IAEA and has signed and ratified both the NPT and a safeguards agreement. This means that the Swedish state has committed itself not to produce nuclear weapons or contribute to other countries' production of nuclear weapons. The IAEA conducts inspections to verify that the treaty is followed, and the Swedish government regulatory body, the Swedish Radiation safety Authority (SSM), is a national organization with responsibility for verifying that the treaties are observed. The work of the SSM is regulated by Swedish legislation and the regulatory systems that have been developed in response to the demands of the IAEA and national requirements.

Sweden is also a member of the European Union since 1995, and this means that the EU conducts surveillance and control of Swedish nuclear technical activities. The body that handles this assignment is the European Commission, through the offices of EURATOM Safeguards. The European Commission in its turn has a treaty (INFCIRC/193) and an agreement (New Partnership Approach) with the IAEA, which means that these two supranational organizations work together, and in some cases their operations are coordinated so as to avoid duplication of work. The standards and rules that Sweden follows in this regard are regulated by the Treaty of Europe and the NPT treaty and appurtenant safeguards agreements.

Article IV concerns the right of NPT signatory states to have access to nuclear materials for the purposes of conducting research or producing nuclear energy for civil use. As stated in item three above, the objective of the NPT is to promote peaceful development of nuclear energy for NPT signatory states, and it is exactly this right to peaceful development of nuclear energy that Iran asserts today when other countries accuse Iran of acquiring nuclear capacity with the aim of developing nuclear weapons. Since civil and military development of nuclear capacity overlap to a large degree, experts and researchers with knowledge of this issue maintain that Iran is taking advantage of the NPT treaty in order to buy and in other ways acquire nuclear materials

[33] Ibid., p. 94 et passim.
[34] https://www.iaea.org/publications/documents/treaties/npt

and equipment for the purpose of producing nuclear weapons. The NPT treaty is, after all, based on the principle that the signatory parties will voluntarily live up to their obligations, even though there is also a measure of control and supervision involved (see chapter 6 for a discussion of how safeguards work in practice).

Article VI deals with a controversial obligation, namely, the promise made by the nuclear states that they would actively promote nuclear weapons limitations and nuclear disarmament. It has been decided that a conference will be held every five years with the aim of evaluating and improving the NPT system. In addition to considering proposed measures for reducing global nuclear arsenals and bringing about nuclear disarmament, these conferences would also serve the purpose of assisting non-nuclear states in developing civil nuclear energy.

Problems along the Way – India and Israel

In 1974 India conducted its first nuclear weapons test. India, to be sure, had not signed the NPT (and still hasn't), but nevertheless this event was considered a major setback for the intentions behind the non-proliferation treaty. The plutonium in the Indian nuclear device came from a so-called CIRUS reactor which Canada had supplied. This was the first time that a nuclear weapons test had been carried out with nuclear materials obtained from a reactor which, according to the Indian-Canadian agreement, was to be used exclusively for peaceful purposes. Canada protested but to no avail. Several countries now questioned the effectiveness of the non-proliferation regime. The United States, for instance, pointed to Article III.2 of the Non-proliferation Treaty, which deals with broadly defined issues of export control, and claimed that it didn't work as intended. The Indian nuclear weapons test also led to the setting up of a new export regime, the Nuclear Suppliers Group (NSG), in 1977, which was aimed at strengthening export controls (for more on the NSG, see chapter 4).

Another problem for the NPT regime arose on 7 June 1981, when Israel bombed and destroyed a test reactor in Iraq, the Tumuz I, which had been supplied by the French. Israel suspected that the reactor was being used for producing weapons-grade nuclear materials. Iraq had signed and ratified the NPT and the destroyed facility was placed under IAEA safeguards. The UN Security Council decided on 8 June that Israel must pay damages to Iraq, and that the state of Israel must accept IAEA safeguards for all its nuclear activities. The latter demand should be seen in the light of the fact that a growing number of countries and researchers in the nuclear field had begun assuming that Israel had acquired nuclear weapons. Israel has never admitted to this, but most experts in the field are in agreement that the country has nuclear weapons capacity. The US-based Israeli historian Anver Cohen, for example, has claimed that Israel possesses circa 100 so-called tactical nuclear weapons. Moreover, Israel has not signed the NPT treaty.[35]

In September 1981 the IAEA General Conference voted to cut off all technical assistance to Israel. It was further decided that, unless it acquiesced to the Security Council's decision, Israel would be excluded from the IAEA. Israel was given one year to conform to this decision. It soon became apparent, however, that Israel would not agree to these conditions. The United States, as the single largest contributor to the IAEA, threatened to leave the organization if Israel was expelled. After a good deal of diplomatic manoeuvring, the

[35] Anver Cohen, Israel and the Bomb. New York: Columbia University Press 1998.

newly installed Swedish IAEA general secretary Hans Blix managed to keep both Israel and the United States in the IAEA.[36]

To sum up the period 1957-1990, arms control and non-proliferation were the dominant approaches in the international efforts to deal with nuclear weapons. In the beginning of this period, United States and the Soviet Union discussed at different international meetings how the arms race and proliferation could be reduced. Initially, nothing of substantial value came out of those talks. The Cuban missile crisis in 1962, however, changed the attitude of the super powers since the conflict almost lead to a nuclear war. As a result, both US and Soviet decision makers understood that they must take actions in real terms to avoid that the arms race and risk of proliferation would lead to an uncontrollable situation. As a result, the Test Ban Treaty was signed in 1963 which prohibited all nuclear detonations except for those underground. The signing of the Test Ban Treaty was viewed as a great success in the efforts to create a more robust international system based on legally binding agreements. The superpowers were now involved in the process and great hopes were invested in strengthening the international order and to prevent further proliferation of nuclear weapons. All those discussions, initiatives and negotiations ended in the signing of the NPT in 1968 and the ratification process in 1970. Several states gave up their plans to acquire nuclear weapons. In this process, the term disarmament was transformed from its original meaning to abolish nuclear weapons completely to be equivalent with nuclear non-proliferation and arms control. In this respect, the NPT allowed the nuclear weapons states who are parties to the agreement to keep the nuclear weapons even though Article VI stipulates that they should "pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control".

After the Cold War: The Period 1991-2021

The collapse of the Soviet Union and the end of the cold war in the beginning of 1990s changed the prerequisites to establish a more stable international security order. Now it seemed that the UN and the world community could work the way the new international system was intended to function shortly after the Second World War. The conflict between East and West was gone and with that all the obstacles that inhibited the UN and the Security Council to create a safer and more peaceful world. In the NPT context that meant that the time was ripe for pushing for the realization of the Article VI, the only aspect that hadn't been tackled in an otherwise rather successful development since the signing of the NPT in 1968. A number of states which had theretofore entertained plans for acquiring nuclear-weapons capability – such as Argentina, Brazil, Sweden, Switzerland, and West Germany – had now signed and ratified the NPT treaty. True, India and probably Israel too had acquired nuclear weapons, but they were not part of the NPT system. They were regarded as exceptions to an otherwise well-functioning NPT regime. An overwhelming majority of the world's states had, after all, signed the treaty. On top of that positive development, Belarus, Kazakhstan and Ukraine became nuclear weapon free states during the first years in the post-cold-war-world. All those three states gave up their nuclear weapons status voluntarily after the break down of the Soviet Union. Next step in this positive development was to deal with the disarmament in its original meaning, namely to strive for general and complete abolishment of nuclear weapons. This issue became a central question during the NPT review conferences in the 1990s. For example, the 1995 conference focused on the obligation set forth in the NPT

[36] Fischer, p. 106 et passim.

treaty to "cease the nuclear arms race," which also included a ban on nuclear weapons tests and negotiations on reductions of nuclear arsenals and nuclear disarmament.[37]

But not everything seemed to work perfectly in the NPT regime. When it became obvious that Iraq, which had signed the NPT and also had a safeguards agreement in force, managed to deceive the IAEA, it became evident that the control system did not fully work. In the aftermath of the Persian Gulf War of 1991, UN inspectors found that Iraq had built facilities for clandestine nuclear weapons production. The system that had been in force up until then was largely based on trust between the individual states and the IAEA in that it was only the nuclear materials of which the states had declared possession that could be subjected to inspections. If a state were pursuing secret nuclear weapons production outside of the areas subject to inspections, then the IAEA would have great difficulty detecting this. The discoveries in Iraq prompted the UN Security Council to declare that proliferation of nuclear weapons constituted a threat to international peace and security, and to envisage measures to be taken on the basis of IAEA reports of NPT treaty violations. General Secretary Hans Blix spoke of creating a new safeguards system with "more teeth." In February 1992 the work of improving the safeguards system began. The next year, North Korea stopped the IAEA from carrying out necessary inspections. Investigations had suggested that the declarations which North Korea had supplied to the IAEA were incorrect. At the same year, South Africa, which had also signed the NPT treaty, announced that it had had nuclear weapons but that these had been dismantled. Coinciding with this announcement, South Africa decided to place its fissile material under the IAEA's nuclear materials control. These events brought to the fore the need to strengthen the whole NPT regime. The reform work followed two main lines: (1) designing a system that would allow "short-notice" or "no-notice" inspections; and (2) exploring the possibility of conducting various forms of tests in the areas covered by safeguards (so-called environmental sampling) in order to verify that the facilities were being used only for declared activities. At the same time, all member states were asked to hand in "design information" concerning new and modified facilities to the IAEA, aimed at enabling the organization to prevent the secret diversion of nuclear materials.[38] Finally, this work group, consisting of a number of member states, would develop a complementary model for how this improved safeguards system could be worked out. In May 1997, the board of the IAEA approved this Model Additional Protocol (under the designation INFCIRC/540), which constitutes an addition to the model treaty INFCIRC/153. The Additional Protocol involves a number of broadened responsibilities (for the member states) and rights (for the IAEA inspectors), which taken together allow for increased access to information and possibilities for surveillance ("complementary access").

Other setbacks after the cold war, were the nuclear weapon tests carried out by India and Pakistan in 1998 and when North Korea withdrew from the NPT in 2002 and conducted its first nuclear weapon test in 2006. Another negative trend has to do with Iran´s conflict with the IAEA regarding if the state is heading for nuclear weapons or not. Some critics have asserted, for example, that unless the nuclear powers make good on the obligations contained in article VI, it is not reasonable to expect states such as North Korea and Iran to shelve their plans for acquiring nuclear weapons.

Despite those setbacks the disarmament issue was much alive in the international discussion. In 2009, for example, the US President Barack Obama gave a speech in Prague where he said that the United States´ goal is to eliminate all nuclear weapons in the world. Many believed that now the time has come to push for a real disarmament process and several initiatives were taken. One of these initiatives is the Humanitarian Initiative

[37] George Bunn, "The Nuclear Non-proliferation Treaty: History and Current Problems." Arms Control Today. December 2003.
[38] Theodore Hirsch, "The IAEA Additional Protocol. What It Is and Why It Matters." The Nonproliferation Review. Fall-Winter 2004.

that was raised during the 2015 NPT Review Conference. The purpose of the Humanitarian Initiative is to put pressure on the nuclear weapons states to show that they are serious about what they promised to do, namely to fulfil the obligation of Article VI. This process has led to the unique UN convention to ban nuclear weapons, the Treaty on the Prohibition of Nuclear Weapons that was adopted in July 2017. The nuclear weapon states were against the ban treaty movement and they didn´t participate in the negotiations. The nuclear weapon states´ position on the issue is that the way to a nuclear free world is a gradual process and the goal will be reached when the world is ready for that final step. In the eyes of the United States and Russia, this step-by-step approach has been successful given that during the height of the cold war there were around 70 000 nuclear weapons in the world and at present the number is around 15 000.

In the period after 1991, disarmament, meaning general and complete abolishment of nuclear weapons, is back as a central dimension in the efforts to create a safer world without nuclear weapons. A majority of the member states in UN voted for an adoption of a treaty banning all nuclear weapons in the UN in 2017 against the will of the nuclear weapon states. Despite all the positive developments that have been taken place since the end of the cold war, the nuclear weapons states, especially the United States and Russia, are lately moving in opposite direction. Both President Trump and President Biden as well as President Putin have announced that they soon will start producing new nuclear weapons. They argue that they need to modernize their nuclear forces which is an obvious sign of the deteriorating security architecture that was established shortly after the end of the cold war.

If we should try to summarize the period from 1945 until now, it´s fair to say that the NPT regime has worked well in terms of reducing horizontal proliferation. That´s a real success story given the negative expectations in the beginning of 1960s that we could have a world of around 25 nuclear weapon states twenty years later. However, the nuclear weapon states have not demonstrated that they are serious about the commitment to take steps to enable a real disarmament despite the commitments formulated in Article VI of the NPT. Certainly 15 000 nuclear weapons are better than 70 000. On the other hand, 15 000 nuclear weapons are probably enough to eliminate most life on earth.

Nuclear Material Subject to Safeguards

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1 Terminology of Nuclear Physics

1.1 Composition of an Atom

An atom is the smallest part of a material that shows all characteristics of that material.

It is composed of a very small nucleus with clear boundary surrounded by a relatively large cloud of electrons. The size of an atom is in the order of 0.1 nm and the size of the nucleus can be described with a typical radius R of 10 fm (10^{-14} m). Chemical reactions involve the cloud of electrons, whereas nuclear reactions affect the nucleus.

The nucleus consists of N neutrons (n) and Z protons (p). N is the neutron number, Z is the atom or proton number. Z equals also the number of electrons and determines the chemical properties of the atom. The total number of nucleons is given by to so-called atomic mass number A (commonly abbreviated as mass number), for which is:

$A = N + Z$

Where Z and A determine completely the nuclide X, written ${}^{A}_{Z}X$ as or as X-A (because the chemical name X refers unambiguously to Z, e.g. ^{235}U, ^{241}Pu, …). Nuclides can be grouped as:

- Isotopes: These are nuclides with the same atom number Z (with the same number of protons, so that the chemical properties of the atoms are the same), but with different atomic mass numbers A (so different number of neutrons.) (e.g. ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U)
- Isobars: These are nuclides with the same atomic mass number A, but with a different atom number Z and different neutron number N (e.g. ^{14}C and ^{14}N)
- Isotones: These are nuclides with the same neutron number N. (e.g. ^{239}Np and ^{238}U)

1.2 Units in Nuclear Physics

The mass and charge of protons, neutrons and electrons are fundamental constants in nuclear physics, which are expressed in special "microscopic units" in addition to the conventional SI ones.

- One mole of a nuclide is given by the quantity that its atomic mass m indicates. The total number of atoms in one mole of a nuclide is given by the constant of Avogadro N_A=0.06022045 10^{24} atoms per g atom. One mole ^{12}C weighs 12 g. One mole of a compound material contains also N_A atoms. Example: One mole ^{235}U weighs 235.044 g and contains 0.6022045 10^{24} atoms ^{235}U.
- As unit of mass is applied u, the atomic mass unit, which is defined by 1/12 of the mass of one atom of the C-12 nuclide. So, 1 mole C-12 weighs 12 g and 1 $u = \frac{1}{12} \times \frac{12}{6{,}022 \times 10^{23}}\ g = 1.66043 \times 10^{-27}\ kg$. The atomic mass of an isotope is given by the mass of this isotope expressed in u; and the atomic mass of an element is calculated with the average of the atomic masses of the different natural isotopes weighted with the natural abundance. The

atomic mass of some relevant isotopes is given in Appendix 1. Note in this table the very small difference between the atomic mass and the atomic mass number A.

- As unit of charge is applied e the electron charge, that is expressed in conventional units by 1.60210 10^{-19} C. The mass and charge of a proton, neutron and electron can be found in Table 1.
- As unit of energy the electronvolt (eV) or the mega-electronvolt (MeV) is commonly applied. One eV is the energy that an electron accumulates while crossing an electric potential of 1 Volt. In SI units expressed: 1eV = 1.6021 10^{-19} J and Based on Einstein's principle of equivalence between energy and mass $E=mc^2$ the atomic mass unit u corresponds to 931.478MeV

Table 1: Mass and electric charge of proton, neutron and electron.

	Proton	Neutron	electron
Mass (*u*)	1.00727663	1.00866540	0.00054897
Charge (*e*)	+1	0	-1

In fission reactions mass is converted into energy. Whereas protons and electrons are stable particles, a neutron is only stable as a particle bound in a nucleus. A free neutron decays into a proton, an electron and an antineutrino. The mean life time of a free neutron is about 12 minutes. The decay of free neutron does not play an important role in nuclear reactors, because the life time of a neutron in a reactor is of the order of a second.

1.3 Size of Atom and Nucleus

The description of an atom as massive core surrounded by a cloud of electrons illustrates the difference between two scientific disciplines:

- the chemistry that studies interactions between the electron clouds of different atoms
- the nuclear physics that studies the nucleus and the interaction with a nucleus.

The two study objects differ considerably in distance. The radius of an atom is of the order of 10^{-10} m, while the nucleus itself has a radius of the order 10^{-14} m, so a ratio between both of 1 m to 10 km.

Scattering experiments demonstrated that the nucleus of an atom has a clear boundary, contrary to the vague boundary of the atom itself. In addition, the nucleus can be considered as a sphere. The value for the radius of the sphere depends on the experimental conditions, mainly on the energy of the particles in the bundle irradiating the nucleus. The radius of the nucleus seems proportional with $A^{1/3}$ resulting in a direct proportional relationship between the volume of the nucleus and the atomic mass number A. This means that the total number of nucleons per unit of volume is relatively constant. The atomic nucleus shows therefore approximately a constant nucleon density. These observations are similar to those with liquid droplets, which also show a constant density independently of their size. Therefore, a droplet model is formulated, that allowed to explain various phenomena of an atomic nucleus.

2 Nuclear Forces - Binding Energy - Stability

2.1 Nuclear Forces

It is not that remarkable, that some atomic nuclei show certain instability and are subject to radioactive decay, but it is remarkable that most nuclei show a stability despite the strong repulsive Coulomb forces between the protons. The stability of nuclei has to be the result of other forces between protons and neutrons. The natural abundance of the nucleus *H-2* (deuterium) demonstrates the existence of attractive forces between neutron and proton, whereas the natural element *He-3* (helion) suggests analogously the existence of proton - proton forces. The very small distances within the nucleus, of the order of 10^{-14} m yield very repulsive Coulomb forces and require even stronger nuclear forces.

Scattering experiments with alfa-particles from Rutherford indicated that down to a range of the order of 10^{-14} m only Coulomb forces are present, so that the strong nuclear forces are active on a shorter range. This very short range of the strong nuclear forces implies that the protons and neutrons only in each other's direct neighbourhood experience these attractive nuclear forces.

2.2 Mass Defect - Binding Energy

The mass of a nucleus is always somewhat smaller than the sum of the masses of the composing nucleons. The difference is called mass defect:

$$\Delta m = Zm_p + Nm_n - m$$

with m_p, m_n, and m the mass of a proton, a neutron and the nucleus respectively. The mass defect corresponds according to Einstein's relation to a certain quantity of energy Δmc^2, which is called the binding energy ($B.E.$). The binding energy is the energy which has to be delivered in order to split up the nucleus in free nucleons. If the B.E. is expressed in MeV and the mass defect Δm in u, then we can write:

$$B.E.\ (MeV) = 931.48\ \Delta m\ (u).$$

By composing a nucleus with A nucleons, this binding energy is freely released.

The binding energy of ^{235}U equals:

$$\Delta m = 92\ .\ 1.007825 + 143\ .\ 1.008665 - 235.0439 = 1.915u$$

and so is $B.E.$ = 178.4MeV and $B.E.$/nucleon = 7.59MeV.

With the experimental values for the mass of the nuclides the binding energy per nucleon can be represented for all nuclides. Figure 1 represents the binding energy per nucleon in function of the mass number.

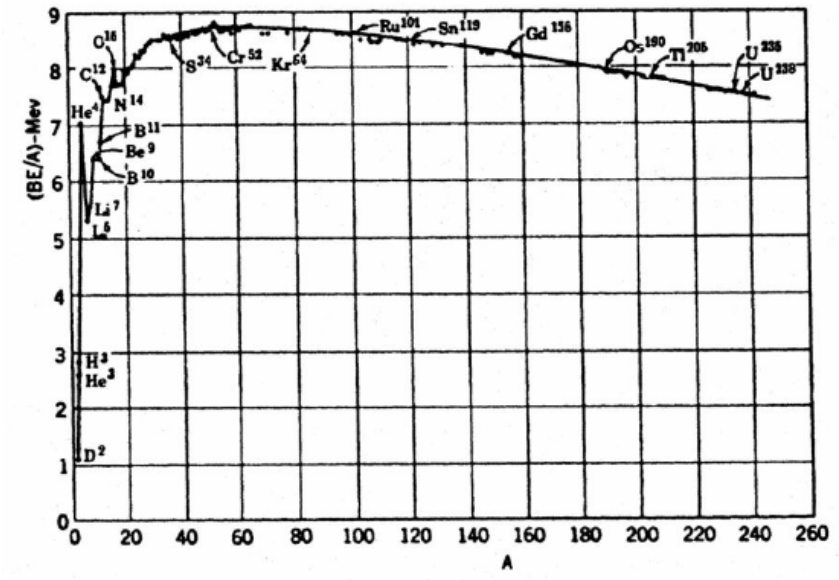

Figure 1: Binding energy (in MeV) per nucleon in function of mass number A.

It can be concluded that:

- the total binding energy increases with increasing number of nucleons
- the binding energy per nucleon is increasing for small mass numbers until a maximum is reached around Fe (A = 56) and then it decreases slowly with further increasing A.

Nuclear reactions in which the nucleons after the reaction are bound more strongly, imply a release of energy, because the nucleon configuration evolves to a larger stability. In a fission reaction a heavy nucleus (^{235}U; ^{239}Pu ; ...) is split up in two fragments, of which the nucleons are bounded more strongly and therefore energy is released. In a fusion reaction, two light nuclei are fusing to one nucleus where nucleons are more strongly bound and again energy is released. The first reaction is industrially used to generate energy, the second promises the same for the future.

2.3 Semi-Empirical Interpretation of the Binding Energy - the Bethe-Weiszäcker Formula

Figure 1 shows that the binding energy per nucleon, except for light nuclei, remains almost constant. This confirms that the nuclear forces are of short range. If the nuclear forces would act on long range, than every nucleon would interact with each other nucleon and the total binding energy for heavy nuclei would be almost proportional to $A(A\text{-}1)$ or A^2. The binding energy per nucleon would be almost proportional with A, which is clearly contradicted in Figure 1. The behaviour of the binding energy per nucleon can be explained by assuming that a nucleon experiences only nuclear forces of its directly neighbouring nucleons, i.e. the short range behaviour of the nuclear forces. In analogy with the droplet model, the nuclear forces can be compared with the molecular forces of a liquid droplet. The nucleons in a nucleus are bound by different forces. The binding energy exists of different terms, i.e.:

- The nuclear forces contribute to the total binding energy with a term proportional to A, which is leading the first so-called volume term.
- The first term implies that each nucleon is surrounded equally by other neutrons, which is not the case at the surface (cfr. analogon of a liquid experiencing a surface tension). This needs a correction

that is proportional with the number of nucleons that are present at the boundary (surface) of the nucleus (sphere), i.e. proportional with R^2 or $A^{2/3}$, which is introduced as the so-called surface term.

- A second cause for reducing the binding energy is the Coulomb repulsion between protons, an electromagnetic force with long range effect. Assuming that the proton density in a nucleus is constant, this electromagnetic energy contribution can be calculated as $(Ze)^2/R$ under the so-called Coulomb term.
- In stable nuclei a tendency of couple formation between neutron and proton is observed. Most nuclei, in particular the heavy ones, have more neutrons than protons. This surplus of neutrons is needed to compensate the repulsive Coulomb forces between protons by the neutron-proton nuclear forces. The abundant number of neutrons $A-2Z$ cannot form couples with protons, which reduces the stability of the nucleus. This is counted for by the asymmetry term, which is proportional to the abundant number of neutrons $A-2Z$ weighted with their relative abundance $(A-2Z)/A$.
- Finally, experimental results show that nuclei with impair number of neutrons and protons (impair-impair type) are less stable and have a lower natural abundance. This is explained with the stabilizing effect of the pair formation between protons respectively neutrons amongst themselves. In the case of a nucleus of pair-pair type the pair formation is perfectly possible with positive benefit to the binding energy, whereas in the case of a nucleus of impair - impair type, one neutron and one proton cannot form a pair which reduces the binding energy.

The sum of these five terms is known as the empirical mass formula or the Bethe-Weiszäcker formula. Without the Coulomb forces maximal stability would be given for $Z=A/2=N$. The deviation thereof is due to the Coulomb repulsion between the protons, which requires compensation by a surplus of neutrons. This deviation (which becomes more important for larger A) can also be noticed in Figure 2 that represents the nuclide chart with Z in function of N.

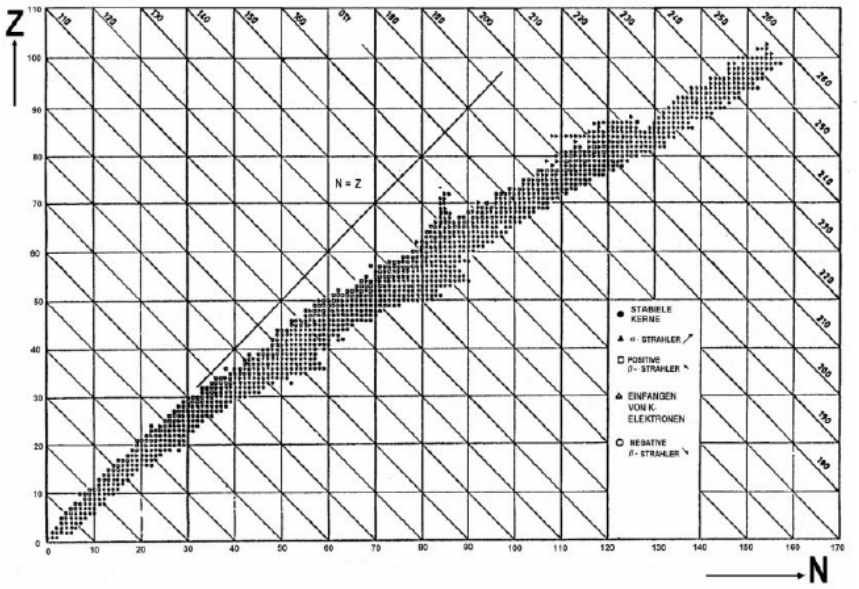

Figure 2: Chart of stable and radioactive nuclides.

3 Excitation and Decay of Nuclei

3.1 Excitation State of a Nucleus

While section 2 considered nuclei in their ground state, a nucleus can also be in an excited state, similar as an atom can. Contrary to atoms, it requires for nuclei more energy to bring an excited nucleon to a higher energy level than to excite a second nucleon. Hence the excitation energy of a nucleus is normally distributed over a number of excited nucleons. This is not surprising when considering the strong coupling between neighbouring nucleons amongst themselves. As a consequence, a nucleus can exist in an excited state at an energy level which is above the binding energy of a single nucleon.

3.2 Radioactive Decay

The time at which an excited nucleus will spontaneously decay, is not predictable. Radioactive decay, a spontaneous disintegration of excited nuclei, is dominated by a statistical law of occurrence. This disintegration is a random process in which the excited nuclei lose energy by emitting radiation in the form of particles or electromagnetic waves. This decay or loss of energy results in a transformation of the initial parent nuclide in a nuclide of different type, called daughter nuclide and is characterised by a decay constant. The decay constant λ is the mean probability rate of nuclides decaying per second s. Experiments with N nuclides demonstrated that λ is constant, independently of time and of macroscopic variables such as pressure, temperature, aggregation state, etc.

The half-life $T_{1/2}$ is the time period after which half of the radioactive nuclei $N/2$ have disappeared. Half of the nuclei $N/2$ present at time t have decayed and are no longer present at time $t + T_{1/2}$.

The presence of radioactive material is detected by measuring the activity. The activity A of radioactive material is defined as the number of disintegrations per s of this material: $A = \lambda . N$.

Originally the activity was expressed in Ci (Curie), which is the activity of 1 g radium. Nowadays the international unit Bq (Becquerel) is used, defined as 1 disintegration per s. Accurate measurements yielded the equivalence 1 Ci = 3.7 10^{10} Bq.

4 Nuclear Fission Phenomena

4.1 Nuclear Reactions and Energy

After the discovery of the neutron in 1932 by J. Chadwick and the induced radioactivity in 1934 by I. Curie and F. Joliot, physicists tried to produce artificially new radionuclides by bombarding different nuclides with neutrons. In particular, the bombardment of uranium yielded a very diverse source of radiation. The explanation remained a relatively long time missing, because of the assumption that radioactivity was caused by the capture of neutrons into the nucleus, and so of isotopes of uranium. Chemical analyses of the German radiochemists, O. Hahn, F. Strassmann and L. Meitner have given proof in 1939 that the radioactivity was caused by much lighter elements than uranium. This meant that uranium was split under the neutron bombardment. Soon after the experiment the nuclear physics community realised that the fission of uranium releases energy and neutrons and that the neutrons released can induce a chain reaction and so a continuous generation of a new energy source. The first nuclear reactor C.P.1 (Chicago Pile No. 1) became critical in 1942 and the problem of a controlled chain reaction was in principle solved. Only afterwards the first atomic bombs exploded.

In this section the fission of heavy nuclides is described from phenomenological point of view. A nuclear reaction between two or more particles occurs if two or more other particles are formed. Nuclear physicists use the notation: $a + b \rightarrow c + d$ or $a(b,c)d$. The nuclear reactions are determined by four fundamental laws of conservation:

1. Conservation of nucleons: the number of nucleons before and after the reaction is the same.
2. Conservation of charge: the sum of the charges of all particles before and after the reaction is the same.
3. Conservation of momentum: the total momentum of the particles before and after the reaction is the same, because there are normally no external forces working on those particles.
4. Conservation of energy: the total quantity of energy before and after the interaction is the same.

In particular the last conservation law is important to generate energy. For a nuclear reaction $a(b,c)d$ this is

$$(m_a c^2 + KE_a + Ex_a) + (m_b c^2 + KE_b + Ex_b) + (m_c c^2 + KE_c + Ex_c) + (m_d c^2 + KE_d + Ex_d)$$

with m_a, m_b, m_c and m_d the mass of the particles a, b, c and respectively d; KE_a, KE_b, KE_c, KE_d the kinetic energy of the particles a, b, c, d and Ex_a, Ex_b, Ex_c, Ex_d the excitation energy of the particles a, b, c and d.

The Q-value of a nuclear reaction is defined by $Q = (m_a+m_b)c^2-(m_c+m_d)c^2$

For a fission reaction: ${}^{235}_{92}U + 1\ {}^{1}_{0}n \rightarrow {}^{98}_{42}Mo + {}^{136}_{54}Xe + 2\ {}^{1}_{0}n + 4\ {}^{0}_{-1}\beta$

The Q-value is determined by $\Delta m = 0.22047u$ and so $Q = 205.4$ MeV. This means that by splitting a uranium nucleus with a neutron a total energy of about 200MeV is released, which is significantly larger than the energy released in an exothermic chemical reaction.

4.2 The Fission Mechanism

Section 2.2 illustrated that the binding energy per nucleon is decreasing from about $A \cong 50$ onwards with increasing mass number A (see Figure 1). As a consequence, the splitting of a heavy nucleus in two lighter nuclei, yields an end-situation in which the nucleons are more strongly bound. Therefore, fission of a heavy nucleus is exothermic. Nuclides such as uranium and plutonium can be split but the mechanism has to be induced. Very heavy nuclei split spontaneously, which explains why nuclides with $Z^2/A > 50$ do not (no longer) exist in nature.

The droplet model helps to understand the fission phenomenon. A schematic representation is given in Figure 3. Starting from a spherical nucleus (Z,A) with radius R (Figure 3a) fission is induced by deformation and two (spherical) nuclei (Z_1, A_1) and (Z_2, A_2) with respectively R_1 and R_2 as radius (Figure 3e) are created. Between Figure 3a and Figure 3e the splitting nucleus undergoes various deformation states (Fig 3b,c,d). Only if the deformation is large enough the ellipsoid might be tied up and consecutively broken up in two parts, which fly apart by the repulsive Coulomb forces.

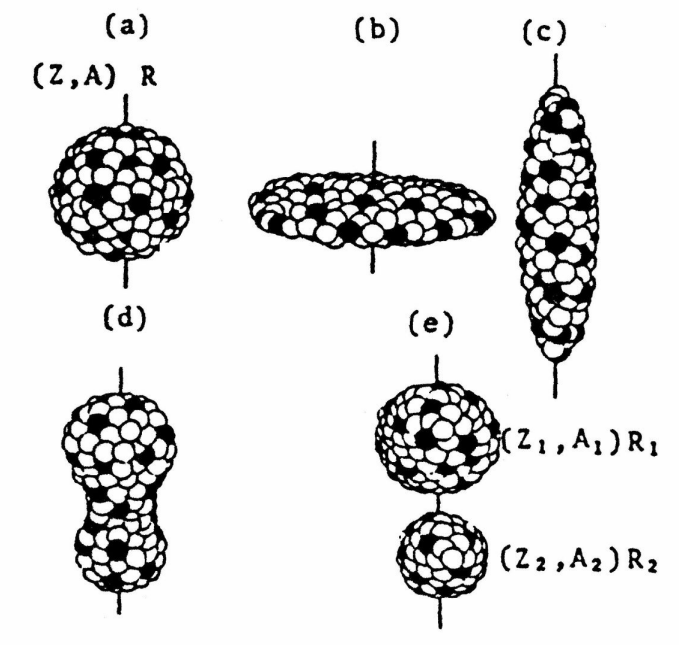

Figure 3: Deformation states of a nucleus which induce fission.

Three different energy states of the splitting heavy nucleus can be distinguished during deformation, as shown in Figure 4.

- *State I:* The attracting nuclear forces dominate the repulsive Coulomb forces. As long as the potential fission fragments are not far enough from each other, additional energy has to be supplied to the nucleus for more deformation.
- *State II:* This is the transition state in which the nuclear forces are losing their dominating character on the Coulomb forces because of their short range effect. This corresponds mainly with the evolving state (d) in Figure 3, where the deformed nucleus becomes tied up.
- *State III*: The energy state in this state is only determined by the classical Coulomb potential between the charged fission fragments. Nuclear forces do no longer play a role because of their short range (in the order of 10^{-14} m).

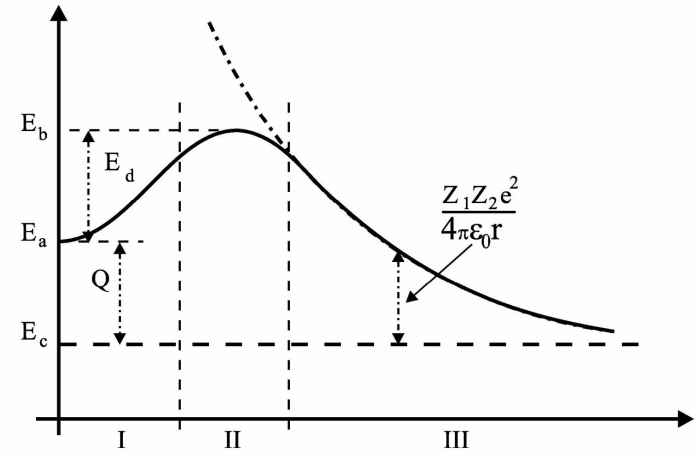

Figure 4: Energy state of a nucleus in function of the distance between the two fission fragments.

A positive Q-value $Q=E_a-E_c$ means that the fission is exothermic. However, the fission is therefore not spontaneously initiated. In the case of Figure 4 and conform to the concept of classical potentials, a minimal excitation energy E_d, $E_d=E_b-E_a$, has to be added to the nucleus. This minimum additional energy E_d is called the fission threshold. Nuclear fission is induced more easily if the fission threshold is lower. The existence of the fission threshold E_d impedes spontaneous fission of heavy nuclei. The magnitude of the fission threshold can be derived by evaluating the deformation energy with the empirical mass formula.

4.3 Fission Induced by Neutrons

From the previous section it can be concluded that a heavy nucleus can split by adding an excitation energy which is larger than the threshold E_d. How can this excitation energy be added to the nucleus? Neutrons are thereto appropriate, because they are neutral and can penetrate the nucleus without suffering of Coulomb repulsion. The binding energy (of this last neutron in the compound nucleus) is then released and brings the compound nucleus in an excited state. The order of magnitude of this binding energy is about 7 MeV. For uranium the threshold is about 6 MeV, so that the absorption of one additional neutron induces fission with high probability.

The consecutive steps are thereby: the nucleus (Z,A) absorbs a neutron and forms an excited compound nucleus of the isotope $(Z,A+1)$[39]. The compound nucleus $(Z,A+1)^*$ splits or loses the excitation energy by emitting an α-particle, a β-particle or a γ-photon.

When a neutron approaches a nucleus, without velocity (or with negligibly small velocity), than the potential energy remains constant, i.e. the ground energy state of the nucleus (Z,A) and the neutron energy (at rest or almost at rest), until the neutron starts experiencing in direct vicinity of the nucleons the nuclear forces. The strongly attractive nuclear forces reduce the potential energy to form a compound nucleus $(Z,A+1)$ at ground state. Hence to keep the total energy of the system constant, the nucleus $(Z,A+1)$ obtains an excitation energy E_x, which equals the binding energy E_n of this latest neutron in MeV given by:

$$E_n = 931.48\,(m_A + m_n - m_{A+1}).$$

The difficulty is the determination of m_{A+1}. The compound nucleus $(Z,A+1)^*$ exists often only a very short time. The empirical mass formula is used to help determining E_n.

For heavy nuclei ($A \cong 230$ to 240) the binding energy of the last nucleon E_n is around 6 MeV with a variation of about 0.5 MeV. Therefore the excitation energy, provided by the capture of a neutron differs for different isotopes by about 1MeV: This is sufficient to distinguish isotopes that are more easily split than others.

- A nuclide for which $E_n > E_d$, is thermally fissionable. The absorption of a thermal neutron, i.e. a neutron with a negligible kinetic energy suffices to induce fission. (Examples of thermally fissionable nuclides: ^{233}U; ^{235}U; ^{239}Pu)
- If $E_n < E_d$, then the absorption of a thermal neutron does not induce fission. Additional excitation energy is necessary, which can be delivered by the kinetic energy of the neutron. Absorption of a fast neutron (with mass m and velocity v) by a nucleus (with mass M, in rest) adds a significant part of the kinetic energy to the excitation energy of the compound nucleus. If $E_x > E_d$ then fission occurs, which is called fast fission. The energy $(E_d - E_n) \cdot (A+1)/A$ is called the kinetic threshold energy of the neutron to induce

[39] The asteriks indicates that the nucleus is in an excited state.

fission. Nuclides for which this kinetic threshold energy is larger than zero, are not thermally fissionable (Example: ^{238}U: for which the neutron needs a kinetic energy of about 1.4 MeV in order to induce a fission).

4.4 Fissile and Fertile Nuclides.

The above mentioned considerations allow a classification of the heavy nuclei as follows:

- *Fissile nuclides*: These nuclides can be split by absorption of a thermal neutron and so are thermally fissionable. Thermal neutrons are in thermal equilibrium with their environment and have a kinetic energy below 0.5eV, which is negligible for the fission phenomenon. Examples of fissile nuclides are ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu, ... of which only ^{235}U has a natural abundance.
- *Non-fissile nuclides*: For these nuclides the absorption of a thermal neutron does not induce fission. Most of the nuclides (also heavy ones) fall under this category.
  - Nevertheless, a limited number of very heavy nuclides can be split by absorption of a fast neutron (with significant kinetic energy), and are *fast fissionable*. The kinetic energy of the neutron has to be above the threshold. Examples of fast fissionable nuclides are ^{232}Th, ^{236}U, ^{238}U, all plutonium isotopes and actinides. (^{238}U and ^{232}Th have a large natural abundance.)
  - Another special case of non-fissile nuclides are *fertile nuclides*. As mentioned above, the absorption of a neutron in a heavy nucleus does not necessarily cause fission of the heavy nucleus $(Z, A+1)$. Nevertheless, it is not a priori excluded that the nucleus of the isotope $(Z, A+1)$ is thermally fissionable. In other words, it might be that the absorption of a neutron in a nucleus (Z,A) forms a nucleus $(Z, A+1)$ which is fissile. Such nuclides are called fertile because absorption of one (or more) neutron transforms them directly or indirectly into a fissile nuclide. Examples of fertile nuclides are ^{238}U, ^{232}Th, ^{240}Pu because the capture of one neutron leads to the formation of the fissile nuclides ^{239}Pu, respectively ^{233}U and respectively ^{241}Pu.

The most important reactions are presented in Figure 5.

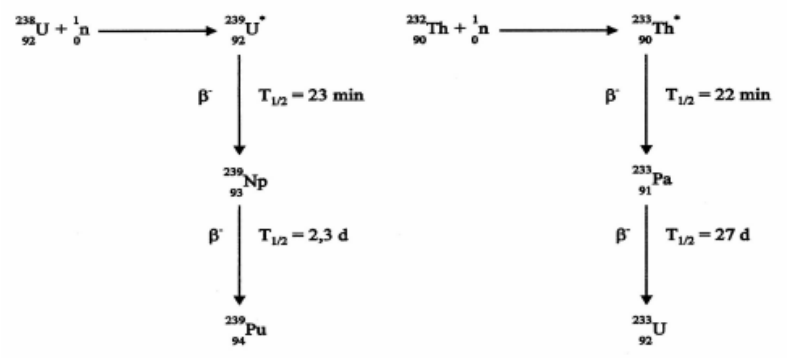

Figure 5: Formation of fissile nuclides from fertile nuclides.

5 Experimental Observations of Nuclear Fission

Experiments on fissions induced by neutrons with a low energy, smaller than the binding energy of a neutron (about 7 MeV), resulted in the following conclusions:

- Once a heavy nucleus reaches the critical deformation, the nucleus is mostly broken up into two fragments, the fission fragments. Since the fission is characterised by two fragments, it is called a *binary fission*. The fission fragments are strongly excited. The excitation energy is removed mainly by emission of two to three (prompt) neutrons within $10^{-12}\ s$ after the fission and the emission of (prompt) photons within $10^{-8}\ s$ after the fission. Binary fission can occur in different ways, and has only to fulfil the criteria that the total number of nucleons in the fission fragments together with the number of emitted prompt neutrons has to be equal to the total number of nucleons of the split compound nucleus (conservation of total number of nucleons).
- The two fission fragments that are remaining after emission of the prompt neutrons are called the two primary fission products. Then secondary fission products are formed by radioactive decay of the primary fission products. The fission products normally are characterised by a too large N/Z-ratio and evolve via β^--decay to a more stable N/Z-ratio. By β^--decay a neutron is exchanged for a proton and an electron accompanied with an antineutrino.
- About 4/5 of the energy emitted at the fission is released as kinetic energy of the fission fragments. The quantity of energy released by fissioning a ^{235}U nucleus depends on the way of fissioning. In example 2 of section 4.1 the Q-value was 205.4 MeV. Although this fission reaction is not at all unique - many possibilities for fissioning exist - it seems that the energy of a random fission of uranium yields about 200MeV. This energy is not completely recoverable. Table 5.2 indicates the distribution of fission energy and its recoverable part.

In summary, the fission of a heavy nucleus yields two fission fragments, two to three fission neutrons, β- and γ-radiation, antineutrino's, and a given quantity of energy.

5.1 The Fission Neutrons

The neutrons promptly emitted are of direct practical importance, because they are needed to maintain a controlled chain reaction. If only one fission neutron is retained from all the released fission neutrons, then this one can again induce one other fission in a controlled way and a controlled chain reaction is realised. The major part of neutrons (> 99 %) is emitted within a time period of $10^{-12}s$. These neutrons are so-called *prompt neutrons*. A relatively small part, fraction β (about 0.2% to 0.65 %), is emitted with a certain delay in time and are called *delayed neutrons*.

- The total number of prompt neutrons emitted depends on the way the nucleus fissions and on the excitation energy of the fission fragments. This number varies from fission to fission between zero to six neutrons. Important for a controlled chain reaction is the averaged number of free neutrons ν per fission. The value of ν depends on the nuclide that is split and on the energy of the neutron that induced the fission (For ^{235}U split by a thermal neutron, ν is typically 2.4.). As a consequence of the large range of possible fission reactions, the kinetic energy of the prompt neutrons shows a continuous spectrum, the so-called fission spectrum $\psi(E)$. This spectrum is defined such that $\psi(E)$ represents the fraction of fission neutrons with an energy between 10 MeV and 0.01 eV. Experimentally the fission spectrum depends very little on the fissioned nuclide and on the energy of the neutron that induced the fission. It shows typically a most probably energy value of around 0.72 MeV and an averaged energy of 2 MeV.

- Although the fraction β of delayed neutrons is small (about 0.0065=0.65%), they play a crucial role in the control of the chain reaction. Delayed neutrons are emitted during the radioactive decay of the excited fission products (mainly via β^--decay coupled with γ–de-excitation). The fission products,

which decay and emit a free neutron, are called mother nuclides for delayed neutrons. The time delay of the free neutron (the time period between moment of fission and emission of neutron) is mainly caused by the β^--decay of the mother nuclide and can last several minutes.

5.2 The Energy Production and Burn-Up

The energy produced by fission that can be recovered is about 200 MeV per fission. This energy is not immediately released, as indicated in Table 2. By the fission products with long half-life, the decay energy is appearing very slowly. In a reactor the major part of the decay energy is of no benefit because the half-lives are often much larger than the life-time of the core in the reactor. The difference between the released and recuperated energy is influenced by the range of the activity. We consider that:

- The travelling distance of the fission fragments is very short (about 10^{-5} m).
- The travelling distance of the neutrons is relatively long (> 0.1 m) and re-used inside the reactor to maintain the chain reaction ongoing.
- The range of the β-rays' penetration is short (in the order of the thickness of an Al foil).
- The range of the γ-rays' penetration is long, so that the recovered portion depends on the place where they are created. The prompt γ-rays and the γ-rays emitted during the decay of the fission products in the reactor fuel (central reactor core) can be recovered.
- For the neutrinos the material is almost transparent, so that they are mainly leaking out of the reactor and their energy is lost.
- The secondary γ-rays are emitted during the neutron absorptions by the different materials in the reactor. Since in average about 2.5 free neutrons are emitted per fission reaction and since only one may induce a new fission, the remaining 1.5 neutrons have to be absorbed somewhere in the reactor. Taking into account the binding energy of 7 - 8 MeV of a neutron, this absorption leads to the excitation energy of about 11 MeV. The excited nuclides lose mainly their energy via radiation.

Table 2: Generated and recovered energy at the thermal fission of a ^{235}U nucleus.

Energy	**Released**	**Recovered**	**Range of activity in reactor**
Kinetic energy of fission products	168 MeV	168 MeV	<0.01cm prompt
Energy of neutrons	5 MeV	5 MeV	>10cm prompt
Prompt γ-radiation	7 MeV	7 MeV	100cm prompt
Fission products' decay **- β-radiation** **- γ-radiation** **- neutrinos**	 8 MeV 7 MeV 12 MeV	 8 MeV 7 MeV --	 <0.1cm delayed <100cm delayed >100cm delayed
Secondary γ-radiation	2-4 MeV	0-2 MeV	100cm delayed
Secondary β-radiation	3-6 MeV	0-3 MeV	<0.1cm delayed
Total	212-217 MeV	195-200 MeV	

In summary one thermal fission yields about 200 MeV, which is about 8.9 10^{-18} kWh thermal power. Almost all nuclear fuels split about 1g fissile material per day to generate 1 MWth. The thermal production of one MW during one day (1 MWd) therefore needs about 1g ^{235}U in the case of a normal pressurised water reactor with UO_2 core.

Theoretically 1 ton heavy nuclides (uranium, plutonium, thorium, ...) can produce about 950.000 MWd thermal energy. This enormous energy potential justifies the large interest to nuclear energy. To quantify the energy that is effectively used in the irradiated or spent fuel, the terminology burn-up of the spent fuel is defined. The burn-up gives an indication on how much (in time and intensity) the fuel has been irradiated. So far, the fuel elements in a reactor are supplying much less energy than theoretically possible, i.e.:

- in normal thermal reactors (pressurised water reactors, boiling water reactors, graphite reactors, ...) the burn-up varies between 5.000 and 35.000 MWd/ton;
- in advanced thermal reactors and in fast reactors (advanced pressurised water reactor, fast breeder, ...) the burn-up varies between 50.000 à 100.000 MWd/ton.

These relatively low values (compared to the theoretical ones) are a consequence of the enrichment in fissile nuclides. In the current reactors almost exclusively the thermally fissionable nuclides are split (mainly ^{235}U). The enrichment in ^{235}U is determining the burn-up. Typical values are:

- about 7000 MWd/ton burnup in reactors fueled with natural uranium (with 0.7% ^{235}U);
- about 35000 MWd/ton in pressurised water reactors (P.W.R.) fueled with uranium that is enriched about 3.5% in ^{235}U;
- about 100.000 MWd/ton in advanced thermal reactors fueled with about 7% enriched U or Pu.

An exception is a fast reactor, which reaches easily 100.000 MWd/ton and which even produces more fissile nuclides than they use. Their enrichment varies between 15 - 20 %.

5.3 Fission Products

The fission of a heavy nuclide shows typically the following characteristics with regard to the fission fragments:

- The fission process creates always two fission fragments. The sum of the partial yields is therefore 200%.
- The yield curve shows clearly two peaks, at A = 95 and at A = 140. The peak yield is about 7% en the width of the peak about 15. Between the peaks a significant valley exists, in particular in the case of thermal fission and the deepest point in the valley indicates symmetric fission. (In every series of 20000 thermal fissions of ^{235}U there is only one symmetric.)
- For heavier nuclides (eg. ^{241}Pu compared to ^{235}U) the yield curve remains double peaked with regard to the deepest point of symmetric fission. The peak of the light group of fission products shifts towards a slightly higher mass number.
- If the energy of the neutrons that induce fission increases (approaching fast fission reactions), the symmetric fission increases importance.

6 Composing a Critical Reactor

Each reactor contains nuclear fuel, structure materials and a coolant that removes the heat of the reactor core. Depending on the energy of the neutrons, that are mainly inducing the fissions, two different types of reactor are distinguished:

- *a thermal reactor*: in this case mainly neutrons with a thermal energy, smaller than 1eV are causing the fissions. These reactors are characterised with one additional element in the reactor: the moderator. The fission neutrons, emitted with an energy of about 2 MeV are scattered at the nuclei of the moderator to lose their energy 6 orders of magnitude until about 1 eV;
- *a fast reactor*: in this case the fission neutrons are not slown down and the fissions are mainly induced by neutrons with an energy above 1 keV.

The composition of a thermal reactor is heterogeneous:

- The fuel is commonly manufactured in the form of fuel pellets, which are introduced in a fuel pin. Different fuel pins are combined to form a fuel element or fuel assembly (normally on a 17x17 grid in pressurised water reactors)
- Between the fuel pins the moderator is introduced. In the case of a solid moderator (e.g. graphite reactors) the moderator is penetrated to also provide a coolant through it (gas or water). In the case of a liquid moderator (water or heavy water), the moderator takes also the role of coolant.
- A considerable quantity of structure material (steel, zircalloy,...) is present in the core to strictly maintain the geometry. The distance between the different parts is needed to be able to cool and control the geometry.

The composition of a fast reactor is similar to a thermal reactor, except that no moderator is present. The rest of this chapter focuses on a thermal (light water) reactor.

In order to describe the neutron balance in a reactor, consecutive steps for the neutrons are modelled with different factors, as illustrated in Figure 6. The product of these factors is defining the effective multiplication factor K_{eff}. Starting from thermal neutron we arrive after one cycle to K_{eff} thermal neutrons. For a reactor K_{eff} needs to be closely to 1 to keep a stable reactor operation. The different factors are:

1. *The production factor* (η): defined as the number of fast neutrons that are emitted by the fission after absorption of one thermal neutron in the fuel.
2. *The fast fission factor* (ε): the fuel normally contains also fertile nuclides in abundance. The fertile nuclides can be split by fast neutrons (with energy above the threshold). To take into account this fast fission effect, a fast fission factor is defined as the number of fast neutrons that are caused by a fast neutron, which is generated during the fission by the original thermal neutron.
3. *The resonance escape probability* (p): during the slowing down by scattering with the moderator nuclei, it is possible that the neutrons interact with other materials (e.g. fuel), and that some with certain neutron energy might be absorbed. The resonance escape probability defines the probability that a fast neutron can be slowed down till it reaches a thermal energy. In this way, neutrons reach the thermal energy region and can be absorbed again in the fuel if they remained in the reactor.
4. *The fast non-leakage probability* (l_1): If the fast neutrons are approaching the geometric boundary of the reactor core, they might leak away, which is taken into account for fast neutrons with the geometrical factor.

5. *The thermal non-leakage probability* (l_2): Also the thermal neutrons might be residing at the geometric boundary of the reactor core and leak away, which is in a similar way taken in to account.
6. *The thermal utilisation factor* (f): The neutrons, which reached the thermal energy region and which did not leak away, can be absorbed either in the fuel or in other material (structure material, moderator, coolant). Therefore, the thermal utilisation factor is defined as the probability that the thermal neutrons are absorbed in the fuel and not elsewhere.

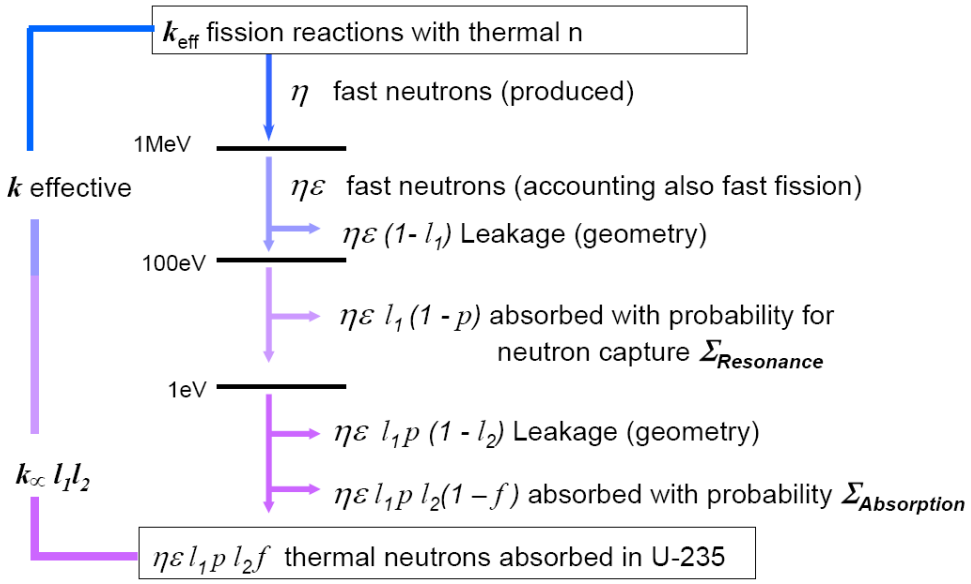

Figure 6: Neutron cycle in a thermal reactor (the ΣResonance and ΣAbsorption indicates macroscopic cross sections, which are the probability for being captured/absorbed).

The total effective multiplication factor k_{eff} is given by $k_{eff} = \eta.\varepsilon.p.l_1.f.l_2$ and the neutron-kinematics of a reactor can be characterised with k_{eff} the reactor has:

- $k_{eff} = 1$: a stationary behaviour is present, the neutron population remains constant and the reactor is critical (controlled chain reaction) with stable operation.
- $k_{eff} > 1$: the neutron population is increasing and the reactor is overcritical (this is also the case of an atomic bomb) with exploding behaviour.
- $k_{eff} < 1$: the neutron population is decreasing and the reactor is subcritical (this is also the case when shutting down a reactor) with an extinguishing behaviour.

The energy production follows the same behaviour as the neutron population.

7 Critical Mass of a Mixture of Nuclear Materials

The critical mass of fissile material is the amount of mass needed for a sustained nuclear chain reaction. It is determined by the minimum volume of the fissile material that houses the mean free path length of a neutron. To cause a fission reaction a neutron traveling through the fissile material should hit with high probability a fissile nucleus and therefore the volume of a critical mass is coupled to the mean free path length of the neutron. The critical mass of a fissionable material depends on: its nuclear properties (e.g. the probability for absorbing a neutron and splitting, that is characterised by the nuclear fission cross-section) and physical properties (in particular the density), its shape and its enrichment. Table 3 gives examples of

bare masses of fissile material. Often such critical mass is surrounded with material where neutrons can be reflected inwards again at the boundary. This reduces the amount of fissile material needed for criticality.

Table 3: overview of estimated critical masses for bare spheres.

Nuclear material	**nuclide**	**Critical mass**
Uranium in metallic spherical form		
highly enriched, weapons-grade U	> 94% ^{235}U	< 50-55kg
highly enriched U	> 50% ^{235}U	< 60kg ±10kg
low enriched U	< 20% ^{235}U	> 800kg ± 40kg
(artificially) bred U	^{233}U	< 10-15kg
Plutonium in metallic spherical form		
Alpha-phase ivory-grade Pu	> 97% ^{239}Pu	< 4kg
Alpha-phase weapons-grade Pu	> 93% ^{239}Pu	< 8-10kg
Delta-phase weapons-grade Pu	> 93% ^{239}Pu	< 10-15kg
Reactor-grade Pu	> 7% ^{240}Pu	> 40-50kg
Elder reactor-grade Pu	> 7% ^{242}Pu	> 100-120kg
Reprocessed spent fuel		
Elder Pu powder with americium	^{241}Am, ^{243}Am	> 50-150kg
Purified americium	> 97% Am^{242}	< 10-20kg
Elder Pu powder with curium	^{246}Cm	> 60-80kg
Purified curium	> 97% ^{245}Cm	< 10-15kg
(artificially) bred curium	^{247}Cm	< 7-12kg
Exotic nuclides produced by selective irradiation		
Neptunium	^{237}Np	< 15-20kg
Californium	^{251}Cf	< 10-15kg

The shape for a critical mass of fissile material is a sphere, because a sphere has the smallest surface to volume ratio. The critical mass of this sphere can be further reduced (about 15%) by surrounding the sphere with a tamper or a neutron reflector of tungsten or steel. In the case of a bare sphere the critical mass is in the order of 50kg for ^{235}U and 8 kg for ^{239}Pu. Bare-sphere critical masses estimated by means of Monte Carlo simulations for some isotopes whose half-lives exceed 100 years are listed in the Table 3.

The critical mass for lower-grade uranium depends strongly on the grade: with 20 % ^{235}U it is over 400 kg; with 15 % ^{235}U, it is well over 600 kg. The critical mass is inversely proportional to the square of the density: if the density is 1% more and the mass 2% less, then the volume is 3% less and the diameter 1% less. The probability for a neutron per *cm* travelled to hit a nucleus is proportional to the density. Saving 1% in diameter means that the distance travelled before leaving the system is 1% less. This is something that is taken into consideration when attempting more precise estimates of critical masses of plutonium isotopes than the rough values given above, because plutonium metal has several different crystal phases which vary significantly in density.

The calculations give accurate input on the number of prompt neutrons that are emitted by thermal fission, fast fission or spontaneous fission. For ^{240}Pu a relative high movability of spontaneous fission exists

(spontaneous fission rate reaches about 1.6 10^6 fissions/(g.h))[40]. This explains why weapons-grade Pu is defined in function of the ^{240}Pu content, i.e. ^{240}Pu < 7% of the Pu-total mass. A too high percentage of ^{240}Pu impedes an easy accurate control of the initiation of a chain reaction and can cause the weapon to detonate prematurely under the form of a fizzle.

A nuclear fission device houses a system which transmutes a subcritical mass into a supercritical mass in a very short time. Two classic methods for assembly (fusion of the subcritical parts) have been used: gun-type and implosion-type. In the simpler gun-type device, two subcritical masses are brought together by using a mechanism similar to an artillery gun to shoot one mass (the projectile) into the other mass (the target). The Hiroshima weapon "Little Boy" was gun-assembled and used ^{235}U as a fuel. Gun-assembled weapons using highly enriched uranium are considered the easiest of all nuclear devices to construct and control.

The other method makes use of the implosion technique, which is more difficult to manage electronically but needs substantially less nuclear material than the gun-type method. A large number of background neutrons are found in plutonium because of the decay by spontaneous fission of the isotope ^{240}Pu. This explains the short time interval between spontaneous neutron emissions in plutonium and the choice by the Manhattan Project scientists to apply the implosion method. This method of imploding the nuclear material to from a critical –even supercritical- mass requires a much smaller amount of Pu. In the implosion method high explosives are arranged to form an imploding shock wave which compresses the fissile material to super-criticality. The "Fat Man" atomic bomb that destroyed Nagasaki in 1945 used 6.2kg Pu and produced an explosive yield of 21-23 kton. Until January 1994, the US Department of Energy (DOE) estimated that 8 kg would typically be needed to make a small nuclear weapon. Subsequently, with the further development of technology and in particular of electronics, the DOE reduced this value to an estimate of 2-4 kg Pu needed for a nuclear device.

In a summary the most common nuclear materials for a nuclear device are high enriched uranium on the one hand and plutonium on the other. In anticipation of the development of both types of nuclear devices, safeguards measures have been developed with quantitative goals, which are worked out in the following section.

8 Significant Quantities in Safeguards

8.1 Significant Quantity for the Nuclear Material of Uranium

For the civil application of most nuclear power plants, it is sufficient to enrich natural uranium (about[41] 0.7% ^{235}U) to a low percentage, 3-5%, in ^{235}U. Light water reactors (pressurised water reactors, boiling water reactors) cannot operate with natural uranium. Heavy water reactors can operate with natural uranium but need to enrich the moderator to heavy water. Graphite reactors operate - depending on the choice of the coolant – with natural or with slightly enriched uranium (typically gas cooled graphite reactors use natural uranium whereas water cooled use slightly enriched uranium).

Different enrichment technologies exist which are built on e.g. diffusors, centrifuges, aerodynamic swirls, calutrons, chemical exchangers, lasers, cyclotron but the most common are centrifuges. The enriching

[40] Chamberlain et al.(1953)

[41] The weight percentage of ^{235}U in the U-ore varies slightly depending on the mine, but natural U is defined with a weight percentage of ^{235}U smaller than 0.72%.

technological element (or most commonly the centrifuge) is typically used in a serial multiplication or so-called cascade, because of the peculiar separation of the ^{235}U component from the ^{238}U component in UF_6 gases based on mass difference between ^{235}U and ^{238}U. If one keeps ongoing with enriching the original gas, it is possible to reach a precious gas, rather small in quantity but with very high percentage in ^{235}U (over 93%), which is of use to military applications. A country equipped with centrifuge technology gains by multiple re-entry of the product in the feed or by changing the cascade configuration (increasing the number of serial stages by connecting some parallel centrifuges in series) the ability to produce weapons-grade uranium.

The quantity of uranium needed to construct a critical mass, depends strongly on its enrichment grade. Therefore, the goal quantity that has to be controlled needs to be specified in function of this enrichment grade. For practical inspection the IAEA defined three categories of uranium that are under safeguards:

- Low Enriched Uranium (LEU) in which ^{235}U mass < 20% of the U mass;
- High Enriched Uranium (HEU) in which ^{235}U mass > 20% of the U mass;
- Ivory grade uranium which is in particular also weapons-grade and in which ^{235}U mass > 93% of the U mass.

Table 4: The three IAEA safeguards goals for nuclear material in the front-end of the fuel cycle.

Material	**^{235}U in LEU**	**^{235}U in HEU**	**Natural U**	**Depleted U**	**Th**
Significant quantity	75kg	25kg	10000kg	20000kg	20000kg
Timeliness	1 year	4 weeks	1 year	1 year	1 year
Probability	For false alarm ≤ 5%; for non-detection ≤ 5%				

The IAEA safeguards goals for uranium nuclear material are defined in Table 4 that shows the restraining measures for higher enrichment of U. The significant quantity reflects the order of magnitude calculated to obtain a critical mass of Uranium at its specified enrichment grade interval. These goals aim to impede proliferation of undesirable uranium devices by timely and efficient detection of a possible diversion of a significant quantity of uranium material.

8.2 Significant Quantity for the Nuclear Material of Plutonium

To avoid proliferation of the implosion-type nuclear devices with Pu, the - by DOE estimated - critical mass quantity of 8kg for plutonium was taken as goal (cfr. Pellaud, 2001). The different characteristics of Pu (in particular the spontaneous fission of ^{240}Pu) have led to 4 categories[42] of Pu, defined in function of the relative weight percentage of ^{240}Pu in the Pu element:

- Reactorgrade (RG) Pu is defined by $^{240}Pu \geq 18\%$ of the Pu mass;
- Fuelgrade (FG) Pu is defined by $7\% \leq {}^{240}Pu < 18\%$;
- Weaponsgrade (WG) Pu is defined by $3\% \leq {}^{240}Pu < 7\%$;
- Ivory grade or supergrade is defined by $^{240}Pu < 3\%$.

[42] Pellaud (2002)

The introduction of mixed oxide fuel for thermal reactors led to a special case of mixture of adding to the U oxide also Pu oxide with Pu≤20% of the mixture weight. Under the current scientific-political approach of safeguards goals, the entire isotopic vector of Pu (giving the composition in all isotopes) is not considered the most practical way for discriminating the Pu in more or less safeguards relevant material. Instead the presence of the nuclide ^{238}Pu is focused on. If ^{238}Pu > 80% of Pu mass, the Pu is excluded from safeguards, as this is a fast decaying nuclide that has mainly applications as battery in spatial research or biomedical products (e.g. pace maker).

The IAEA safeguards goals for artificially produced nuclear material, plutonium and uranium-233 are defined in Table 5. Again the significant quantity reflects the order of magnitude calculated to obtain a critical mass of Pu or ^{233}U. These goals aim to impede proliferation of nuclear (implosion-type) devices by timely and efficient detection of a possible diversion of a significant quantity of this material.

Table 5: The 3 IAEA safeguards goals for nuclear materials, that are produced while breeding and are present (mainly) in the back-end of the fuel cycle.

Material	^{233}U	**FG/RG Pu**	**WG Pu**	**Pu mixtures**	**Pu in irr. F.A.**
Significant quantity	8kg	8 kg	4 kg	3 kg	1 F.A.
Timeliness	4 weeks	4 weeks	1 week	1 year	3 months
Probability	For false alarm ≤ 5%; for non-detection ≤ 5%				

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The Historical Context of the EURATOM Treaty's Safeguards System

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Abstract

This chapter presents the history of the making of EURATOM safeguards system. It describes the treaty's features, which created the safeguards. To approach it, it offers a narrative of the European integration debate during the first decade of the Cold War, and of the coming into force of NPT. It deals with both military and civilian aspects to introduce the historical relevance of the EURATOM safeguards system.

The Themes of the European Integration

In 1948, the hard political struggle between the Soviet Union and the United States crossed Europe. The result was the division of the continent into two areas of influence, and political, economic and social systems. This was an ideological conflict that fought for the hearts and minds of the people: known as the Cold War, the conflict pivoted on nuclear weapon stockpiles and the strategic concept of nuclear deterrence. The epicentre of the European Cold War was in Germany, a nation divided since 1949 into two entities based on the former post-war occupation zones. In the previous year, on 17 March, 1948, France and Great Britain signed a treaty with the three Benelux countries. The treaty is known as the Pact of Brussels and according to the signers, it was created to stop the possible resurgence of a German threat. The communist threat stood as a historical twofold danger in Western Europe governments' perception by taking the shape of both internal subversions elicited by communist parties and the risk of a Soviet invasion.

The issue of German rearmament became a framework cornerstone of the alliances that divided the West from the East on the continent. The line separated countries ruled by communist parties and countries where they were excluded from government or banned. The Western group promoted a series of political initiatives to integrate Europe and to achieve a peaceful and prosperous future. European integration was the condition to receive the United States' commitment for defence, security, and recovery, which was supposed to contain the Soviet threat. At the same time, European integration was a tool to contain the possible rebirth of German power. A significant portion of American leadership supported the European integration project, engaging in an internal debate that would eventually see it victorious against the longstanding US isolationists. Similarly, UK Statesman Winston Churchill and other British influential personalities supported the need for European cohesion to stand against the Russians. The need for integration was also echoed by other European statesmen such as the Italian Alcide De Gasperi, the German Konrad Adenauer, and the French Robert Schuman. Each had their own perspectives and different goals but endorsed the endeavour of the making of a common Europe. The defence and security debates were intertwined with the discussion on economic development and political cohesion because economic development was supposed to dispel social instability and erode the political risk of communists uprising.

The United States government followed their engagement started with the European Recovery Program (the so-called Marshall plan) creating a defence system with the North Atlantic Treaty which was signed in Washington on 4 April, 1949. This treaty addressed Western European governments' concerns toward the Soviet threat and committed the United States to defending Europe. In August of that year, the US atomic

monopoly ended as the Soviet Union had become a nuclear power, immediately giving Europeans more reasons to endorse the North Atlantic Treaty. The newly formed Atlantic alliance established an unprecedented organizational structure that allowed for the creation of permanently deployed armed forces during peace time. Furthermore, the Atlantic organization's creation forced the consideration of integrating West Germany into the Western defence system, which would have meant the German rearmament. Nevertheless, the other track of economic and political integration was the consideration of European cohesion and expected unification; such a kind of integration was supposed to solve the quarrelsome question of German's role in the European defence system. [1]

The ECSC and the EDC

Regarding economic and political integration, the European leaders opted for a sectorial approach that focused on key economic fields. The first was the coal and steel industry. On 9 May, 1950, Schuman proposed establishing a high authority for coal and steel that would have reconciled the needs of France and the West Germany while also paving the way for European consensus with Italy and the Benelux countries regarding production and market of both goods. The main cause of friction between France and Germany was the control of the Saar and Ruhr mining areas. The plan proposed by Schuman eliminated subordination in Saar and Ruhr coal and steel districts and allowed German participation in new coal and steel production. The coal and steel high authority led the European Coal and Steel Community, a supranational organization which had powers over the member states. The authority was charged with managing significant aspects of the coal and steel industries above the member states. Konrad Adenauer responded positively to the proposal, which was extended to other European countries

The Korean War on 25th June of that year, the first outbreak in the peninsula after WWII, increased the demand of steel and pressured Americans to ask negotiation participants for the rearmament of West Germany as an ally in the conflict. The president of the French ministers' council, René Pleven, responded to such growing harshen of Cold War with a plan for the creation of a European defense community, which would have followed the coal and steel community model while the Western governments reached an agreement and created the ECSC. The treaty was approved on 18 April, 1951, and the supranational body came into force on 25 July, 1952, with Belgium, France, Germany, Italy, Luxembourg, and the Netherlands (called "the Six", as member states). Jean Monnet, a French international officer and staunch supporter of Europeism, was appointed President of the Community High Authority.

In fact, the community created a common market for the steel industry, which regulated the respective shares of production of various countries as a framework for the development and modernization of the whole European industry. The ECSC High Authority was composed of nine members with a maximum of two for each member state. To balance it, the Council of Ministers was also established. It was made by the ministers of the member states' governments because Commission members were not subject to national governments. The Council liaised the High Authority with national governments. A court of justice was also created to resolve disputes that arose under the treaty between the High Authority, the member states, and the stakeholders. [2]

The relevant point for us is the first statement of verification principle established by the ECSC treaty. Indeed, the treaty contained the ability for the High Authority to control the actual production of carbon and steel industries in the member states through inspections. By doing so, the High Authority assured members against other member's possible misconduct. Because the High Authority was independent, every government trusted the quality of its inspections. This verification model set the precedent for the atomic energy

community's safeguards. The member states were assured that their neighbors would not turn the ploughshares into swords.

The Six tried to apply the same supranational model to the creation of a European defense community (EDC) because it was demanded by the Americans to allow them to politically and strategically commit to the defense of Western Europe from the risk of a Soviet invasion. However, the French Parliament rejected the EDC in August 1954, [3] so the British took the initiative and pushed the Brussels Pact toward creating the Western European Union (WEU), which was an organization with West German participation without any supranational features. [4]

A Nuclear Driver for the European Union

The ECSC had demonstrated Europe's willingness to integrate a strategic sector according to the supranational principle. Conversely, the EDC had showed the limits of this kind of integration when it involved a branch as sensitive as defense. Because the EDC was supposed to be the main step forward to European unification, after its fumble, the whole process broke down. The European governments looked for a driving force to resume the process of European integration and found it in the nuclear energy and its promising power production. After the death of Soviet dictator Josip Stalin on May 1953, the international tensions seemed to release, as in December of same year, US president Dwight D. Eisenhower delivered the "Atoms for Peace" speech to the United Nations general assembly, which committed his government to international cooperation relating to the peaceful uses of atomic energy. The following Atomic Energy Act of 1954 included any future bilateral cooperation agreement with the United States. The basic mission of the act was the peaceful transfer of technology. As a part of the act's peaceful goal, transferring any information related to weapon design or fabrication was forbidden. To verify the compliance of the partner States, the United States government can subject all transfer recipients facility inspections and enclose this caveat in the agreement offered to the Europeans. [5]

The term "horizontal proliferation" was not yet the expression used to define the acquisition of nuclear weapons by other states than the three nuclear powers of those days. Nevertheless, it was the top priority in the US atomic policy, as the American government called it "the fourth country problem" [6]. Among the Six European States, France was the fourth country on the list. The US promoted peaceful uses of nuclear energy as an indirect way to slow down the nuclear weapons project by other states. As the non-nuclear states needed technology and materials to achieve nuclear weapons, they looked for international cooperation to fill the gap. If the US, the more advanced nuclear state, limited transfers for peaceful uses only, the recipient state was restricted to peaceful utilisation, making the weapon projects more difficult.

Louis Armand, a prominent figure in French nuclear sector, was conducting a study on behalf of the OECD that examined the future production of nuclear energy on the continent. The study referenced the advantages an authority for an integrated management of nuclear development in Europe would bring. In 1955, Jean Monnet resigned from the post of High Commissioner of the ECSC, and he began to promote the creation of a European Community for Atomic Energy.

The governments of the Six convened at a conference from 1 to 3 June, 1955 in Messina, Sicily, to resume the European integration projects. They discussed the topics of a nuclear community and of a common market. After long debating, French Foreign Minister Antoine Pinay agreed with the other delegates to create technical and politically mixed group that would run the negotiations toward both the communities.

Thus, the Six established an Intergovernmental Committee, better known as the Spaak Committee, as it was chaired by the Belgian statesman Paul Henry Spaak. It worked throughout the summer of 1955 to bring

together the negotiating positions of the Six; a British delegation participated as an observer in the early stages of the Spaak committee, but it left because the British government disagreed with the strong supranational features of the planned integration.

The Spaak committee produced a report which carefully presented the atomic energy community, acronym EURATOM. The first issue was the thorniest: addressing the risk of military diversion of fissile fuels distributed by the community for peaceful purposes. The second issue was related to the preferable way to create a common supply system of fissile fuel, a request that had long been advocated and supported by the French delegation.

During the rounds of negotiations following the report presentation, the US government clearly and openly endorsed the project of a European atomic community. The reasons for the US support of EURATOM were clear: making West Germany an organic element of the Western coalition, helping the Franco-German relations, fostering the spreading of nuclear technology in a peaceful direction, and quickly developing a solid nuclear power industry in Europe as client of the US nuclear complex. [7]

The Suez Crisis and the Committee of the Three Wise Men

In October 1956, after the nationalization of the Suez Canal by Egyptian government, France, Great Britain and Israel responded with a military expedition to restore the former ownership of the Canal. Both US and USSR exposed the action, forcing the three to withdraw. The War caused a blockade of homonymous Canal, with an immediate destabilizing effect on the fuel market and on the power production costs. The reconstruction of the continent after the World War II had been based on the extensive import of Middle Eastern crude oil, which seemed free of any risk of interruption. The war strongly pushed the French government toward achieving an autonomous nuclear armament to restore the international role of the French republic after the Suez political defeat.

The Suez crisis was a disturbing point in the transatlantic relations between the United States and the European powers: after it, from both sides of the ocean, it appeared necessary to strengthen – or reconstruct the bond of Atlantic solidarity. Within the US leadership, concernments arose on the risk of European withdrawing from the atomic community project, which was caused by the United States' position during the Suez war. The Six appeared much more likely to give birth to forms of increasingly bland nuclear cooperation rather than to commit to fostering a supranational integration. This possibility meant that western European states would ask the US for bilateral agreements for fissile materials; therefore, not endorsing the US position on the creation of a single continental supply agency in the framework of a European atomic energy community which would be committed to peaceful uses of the technology.

Just before the war, on 20 September 1956, the representatives of the Six agreed for the creation of a "Committee of Wise Persons" that was mandated to establish a viable program to produce Atomic energy. Europe would reduce dependency on foreign energy sources by obtaining the support from British US technology. The Committee included Louis Armand—Director General of Railways and member of the CEA, Franz Etzel—German Member of Parliament and vice president of the High Authority of the ECSC, and Francesco Giordani—a chemist and Chairman of the Italian National Research Council. Monnet was convinced that once the treaty was signed, US support of EURATOM would have an effect comparable to that of the Marshall Plan.

On 21 December, the US government issued a press release officially inviting the three European experts to the US to have conversations with government officials and CEOs of major industrial corporations. On 4 February 1957, the Three Wise Men arrived in Washington to collect unclassified information technologies

based on American civil programs, their costs, and to discuss several research programs that interested both sides.

On 8 February 1957 a joint statement was released, emphasizing that the exchange of experience and technical progress would strengthen the two sides of the Atlantic. A joint group of experts was also set up. They were appointed by the Three Wise Men and by the American Atomic Energy Commission (AEC) and were instructed to continue the study of the technical problems caused by implementing the program.

The visit of the Three Wise Men in the United States marked a turning point in the American attitude toward the nuclear military ambitions of the Europeans. The State Department and the AEC eventually accepted the caveat of national nuclear militaries to be ran outside of the community cooperation and removed their position requiring a renounce of nuclear weapons by the Europeans as a prerequisite for the participation in the community. Previously in 1954, the Federal German Chancellor Konrad Adenauer had committed the German government to renounce to nuclear, chemical, and biological weapons, while the Italian government never endorsed a national nuclear military program that was technically feasibility. The French government was the only one that had both the technical capability and the political willingness to enter the nuclear club, despite the technical gap the French nuclear complex had to fill to achieve nuclear weapons. [8]

The Treaty

On 25 March 1957, the two Treaties of Rome, established the European Economic Community and the European Atomic Energy Community, called EURATOM. The EURATOM treaty was composed by a preamble and 225 articles in six titles, plus annexes and protocols, and it came into force from 1 January 1958. As stated in its preamble, the Six recognized "that nuclear energy represents an essential resource for the development and invigoration of industry and will permit the advancement of the cause of peace". The treaty in article 1 of EURATOM was stated "to contribute to the raising of the standard of living in the Member States and to the development of relations with the other countries by creating the conditions necessary for the speedy establishment and growth of nuclear industries". The EURATOM Commission had the same supranational features of the ECSC High Authority.

The development of a nuclear industry involved multiple aspects: it assumed the creation of a common continent-wide market of nuclear technologies, which would put no restrictions on the circulation of knowledge, human resources, and capital. EURATOM should conduct research, provide access to the necessary fissile fuels and technological components, encourage and facilitate investments, and promote the sharing of technological information.

As for nuclear development, the Community research effort was built around two main ideas: the coordination of national research programs of the Six—which remained autonomous and independent within the Community framework—and the creation of a joint research program that had to be "complementary" to the technological progress made by the scientific community. The EURATOM Commission, responsible for the so-called "principle of coordination", oversaw these activities; in other words, the Community avoided or limited unnecessary duplication of research through a strong connection with the national players of nuclear research. In member countries, EURATOM loans money to projects related to nuclear power generation and the nuclear fuel cycle.

The EURATOM Commission developed the Community nuclear research activities with the Joint Nuclear Research Centre (JNRC) and with the allocation of research contracts. The JNRC was comprised of four research centres: Ispra (Italy), Petten (the Netherlands), Geel (Belgium) and Karlsruhe (Germany). The JNRC

was the primary tool to run the Community research. The allocation of research contracts, conversely, allowed EURATOM to contribute external research projects that were of common benefit to the Six.

EURATOM ensured the sharing of nuclear information among all actors, state and none, who were active in the sector, as feature of the common nuclear market for the community established from 1 January 1959. The Six had a common external tariff and the freedom to exchange technology and manpower. Thanks to the exchange or technology and manpower, industries could negotiate purchases and sales of minerals, fuels and technologies with greater freedom and a significant reduction in price. [9]

A safeguard system intertwined all these tasks, ensuring the peacefulness of the community actions.

The Safeguards

Title two, Chapter seven of the treaty entailed the core of EURATOM safeguards system. According to Howlett, it follows the framework of safeguards stated in the United States model of nuclear cooperation agreement, and the American concepts of international control of nuclear energy. [Howlett, 90-1] The obvious difference is that the subject enacting the safeguards was EURATOM Commission, a supranational authority and not the recipient state or the provider.

Article 77

Under this Chapter, the Commission shall satisfy itself that, in the territories of Member States:

a) ores, source materials and special fissile materials are not diverted from their intended uses as declared by the users;

b) the provisions relating to supply and any particular safeguarding obligations assumed by the Community under an agreement concluded with a third State or an international organisation are complied with.

Article 78

Anyone setting up or operating an installation for the production, separation or other use of source materials or special fissile materials or for the processing of irradiated nuclear fuels shall declare to the Commission the basic technical characteristics of the installations, to the extent that knowledge of these characteristics is necessary for the attainment of the objectives set out in Article 77.

The Commission must approve the techniques to be used for the chemical processing of irradiated materials, to the extent necessary to attain the objectives set out in Article 77.

Article 79

The Commission shall require that operating records be kept and produced in order to permit accounting for ores, source materials and special fissile materials used or produced. The same requirement shall apply in the case of the transport of source materials and special fissile materials.

Those subject to such requirements shall notify the authorities of the Member State concerned of any communications they make to the Commission pursuant to Article 78 and to the first paragraph of this Article.

The nature and the extent of the requirements referred to in the first paragraph of this Article shall be defined in a regulation made by the Commission and approved by the Council.

Article 80

The Commission may require that any excess special fissile materials recovered or obtained as by products and not actually being used or ready for use shall be deposited with the Agency or in other stores which are or can be supervised by the Commission.

Special fissile materials deposited in this way must be returned forthwith to those concerned at their request.

Article 81 defined inspections, which follows the model of inspections as stated in the ECSC treaty, but with a broader meaning. Indeed, the ECSC treaty in the chapter 4, article 65, defined inspections as a tool of the Commission for the control of the production. For EURATOM, the same framework was applied with the aim of checking any diversion from the peaceful means declared by the member states.

Article 81

The Commission may send inspectors into the territories of Member States. Before sending an inspector on his first assignment in the territory of a Member State, the Commission shall consult the State concerned; such consultation shall suffice to cover all future assignments of this inspector.

On presentation of a document establishing their authority, inspectors shall at all times have access to all places and data and to all persons who, by reason of their occupation, deal with materials, equipment or installations subject to the safeguards provided for in this Chapter, to the extent necessary in order to apply such safeguards to ores, source materials and special fissile materials and to ensure compliance with the provisions of Article 77. Should the State concerned so request, inspectors appointed by the Commission shall be accompanied by representatives of the authorities of that State; however, the inspectors shall not thereby be delayed or otherwise impeded in the performance of their duties.

If the carrying out of an inspection is opposed, the Commission shall apply to the President of the Court of Justice of the European Union for an order to ensure that the inspection be carried out compulsorily. The President of the Court of Justice of the European Union shall give a decision within three days.

If there is danger in delay, the Commission may itself issue a written order, in the form of a decision, to proceed with the inspection. This order shall be submitted without delay to the President of the Court of Justice of the European Union for subsequent approval.

After the order or decision has been issued, the authorities of the State concerned shall ensure that the inspectors have access to the places specified in the order or decision.

The Commission, which relies on the Court of Justice for the disputes with member states, controls the recruitment of inspectors and the imposing of sanctions. The EURATOM Commission had no precedent in the nuclear regulation realm.

Article 82

Inspectors shall be recruited by the Commission.

They shall be responsible for obtaining and verifying the records referred to in Article 79. They shall report any infringement to the Commission.

The Commission may issue a directive calling upon the Member State concerned to take, by a time limit set by the Commission, all measures necessary to bring such infringement to an end; it shall inform the Council thereof.

If the Member State does not comply with the Commission directive by the time limit set, the Commission or any Member State concerned may, in derogation from Articles 258 and 259 of the Treaty on the Functioning of the European Union, refer the matter to the Court of Justice of the European Union direct.

Article 83

1. In the event of an infringement on the part of persons or undertakings of the obligations imposed on them by this Chapter, the Commission may impose sanctions on such persons or undertakings.

These sanctions shall be in order of severity:

a) a warning;

b) the withdrawal of special benefits such as financial or technical assistance;

c) the placing of the undertaking for a period not exceeding four months under the administration of a person or board appointed by common accord of the Commission and the State having jurisdiction over the undertaking;

d) total or partial withdrawal of source materials or special fissile materials.

Of course, the power must align with the rules regarding nuclear military programs agreed by the Six. The article 84 reinforced the exemption from safeguards of the military programs. It is a "defence clause" which excluded the safeguards of nuclear materials tied to defence tasks, as well as those outside military areas. Renouncing nuclear weapons' achievements or goals was not required to join EURATOM. The EURATOM treaty requires members to promote peaceful uses of nuclear energy and to not divert the resources of the community to military applications. This required states to communicate what materials were employed for defence. Those material are exempted from safeguards and removed from the EURATOM development system.

Article 84

In the application of the safeguards, no discrimination shall be made on grounds of the use for which ores, source materials and special fissile materials are intended.

The scope of and procedure for the safeguards and the powers of the bodies responsible for their application shall be confined to the attainment of the objectives set out in this Chapter.

The safeguards may not extend to materials intended to meet defence requirements which are in the course of being specially processed for this purpose or which, after being so processed, are, in accordance with an operational plan, placed or stored in a military establishment.

As we can see, the EURATOM treaty distinguished between special fissionable materials and other nuclear materials and ores. EURATOM exerted the right of exclusive ownership on fissionable materials ^{235}U, ^{239}Pu and ^{233}U. All others are nuclear materials, which the Community has the right to cover.

Thus, Title two, Chapter six dealt with the supply of nuclear materials, special or other ones. Chapter eight dealt with the Community's property and rights regarding the special fissile materials in the territories of the member states and enforcing and verify the compliance by authority. In this way,

the EURATOM safeguards system was the only one covering the entire nuclear fuel cycle, from mining to final reprocessing. The general provisions of Title five gave EURATOM the legal capacity to run the inspections in the territories of the member states.

The US-EURATOM Agreement

In 1958, the United States government prepared the agreement with EURATOM. This was a cornerstone for the effectiveness of the Community's action and for the nuclear policy of the United States. In the message delivered by Eisenhower to the Congress, pending the approval of the agreement, he outlined a goal for the next five years in Europe: about one million of kilowatt of installed nuclear capacity, from reactors developed in the United States. But this goal would be tied to an effective control of the technology transfer, and the right receiving spent fuel from Europe, as well as a request of compatibility between the EURATOM safeguards system and the IAEA's one.

The Congress of the United States eventually approved the agreement on 27 August 1958. The United States provided the Community with technology and a supply of ^{235}U. EURATOM committed to refrain from using the technology and the nuclear materials provided by the United States for military purposes, directly or as a by-product. The same items were not transferred by the Community to third parties without the authorization of the United States.

The requirements were strictly binding to avoid any current or future diversion of the technology and of the nuclear materials from research or power production. But it acknowledged the right of self-inspections for the Community: this fostered the recovery of transatlantic trust after the Suez crisis. Thus marking an exception in the framework of the United States nuclear cooperation agreements despite the disappointment of the US general director of the IAEA, Sterling Cole.

Cole saw the right of self-inspection as limiting the authority of IAEA [Krige]. Actually, the agreement requested the integration with the IAEA safeguards. The issue of integrating the two safeguards' systems was raised with the debate on the Non-Proliferation Treaty. On May 1962, the agreement was amended, and the United States accepted the reprocessing of the US provided spent elements in the European Community. [10]

The Regulations for Implementing the Safeguards and the Beginning of the Inspections

The implementation of the treaty needed legislative activity to allow the safeguards (and the inspections). In 1959-1960, the EURATOM commission enacted a slot of regulations (No. 2, 7, 8 and 9) to define the safeguard system. They were relevant to the basic technical characteristics of each plant and how it should be communicated to the Commission, and to the nuclear materials accountability, which had to be periodically declared by the various enterprises that have stock or movement of ores, source materials, and special fissile materials

This consistent corpus of rules allowed EURATOM to perform its first inspection, which took place on the April 1960 at Mol, in Belgium. It was focused on material accountancy and control instead of on-site inspection. In February of same year, France had performed its first successful nuclear weapon test. With the growing nuclear industry in EURATOM countries came a growing number of inspections. The amendment to the US-EURATOM agreement of 1962 put the Community in charge of safeguarding the reprocessing of spent fuel. This shifted the inspections and introduced new procedures that enabled them to control the reprocessing plants.

This expansion and improvement of the safeguards caused an increased recruitment of the inspectors. While the first inspectors had a diplomatic or international legal background, the following inspectors came more from technical and scientific careers in the nuclear sciences and technologies.

From the first inspection to 1967, we had 411 inspections divided among the following: research reactors (177), fuel fabrication plants (101), power reactors (53), research centres (50), irradiated fuel treatment facilities (20), and fuel stores (10). [11]

On 8 April 1965 was signed in Brussels the Merger Treaty, also known as the Treaty of Brussels, which unified the executive institutions of the ECSC, EURATOM and the European Economic Community (EEC). It came into force on 1 July 1967, setting out that the Commission of the European Communities should replace the High Authority of the ECSC, the Commission of the EEC and the Commission of EURATOM, and that the Council of the European Communities should replace the Special Council of Ministers of the ECSC, the Council of the EEC and the Council of EURATOM. Although each Community remained legally independent, they shared common institutions (prior to this treaty, they already shared the Parliamentary Assembly and Court of Justice) and were together known as the European Communities.

The Non-Proliferation Treaty and the Enlargement of the Community

The nuclear international situation was continuing to evolve, with the People's Republic of China testing its nuclear weapon in 1964. This elicited the United Kingdom, the United States and the Soviet Union to promote a treaty aimed to limit the horizontal proliferation.

The Non-Proliferation Treaty was open to signatures in 1968. The adoption of NPT marked a very relevant milestone in the history of safeguards, extending them to all the nuclear facilities of the non-nuclear weapons state adherents. But

it renewed the conflict between an international organization, like the IAEA, with an international safeguard system and a supranational organization, like EURATOM, with a regional safeguard system. In 1957, the EURATOM authority overwhelmed the IAEA authority, but the NPT gave the IAEA a new role in the incoming non-proliferation regime, so the EURATOM member states found themselves in the middle of two overlapping safeguard systems. [12]

The US, UK, and USSR, as proponents of NPT, called all nations of the world to adhere but not all nations signed the treaty. Among the Six, the French Republic did not sign the treaty, while the Federal Republic of Germany and the Italian Republic signed in 1969 but waited until 1975 to ratify the treaty. So, when the non-proliferation regime came into power, the only nuclear weapon state of EURATOM (France) did not adhere, and other two EURATOM states delayed its ratification (West Germany and Italy). In this framework, the IAEA opened a negotiation with the EURATOM to ensure the enforcement of the safeguard system. The first round of negotiations occurred during the writing of the treaty. The NPT recognized indirectly EURATOM in its article 8:

> Nothing in this [Non-proliferation] Treaty affects the right of any group of States to conclude regional treaties in order to assure the total absence of nuclear weapons in their respective territories.

Article 3 of the NPT stated the requirements for the safeguard's acceptance by the NNWS. Comma 4 of this article states:

> Non-nuclear-weapon States Party to the Treaty shall conclude agreements with the International Atomic Energy Agency to meet the requirements of this Article either individually or together with other States in accordance with the Statute of the International Atomic Energy Agency. Negotiation of such agreements shall commence within 180 days from the original entry into force of this Treaty. For States depositing their instruments of ratification or accession after the 180-day period, negotiation of such agreements shall commence not later than the date of such deposit. Such agreements shall enter into force not later than eighteen months after the date of initiation of negotiations.

Eventually the Agency and the Community reached an agreement. The INFCIRC/153, enacted by the IAEA board of governors in June 1971, described the agreement between the agency and the adherent states. Articles 78-82 mention the concept of a third safeguarding agent which is functionally independent from member states nuclear material accounting system.

It seemed that the agreement proposed a proxy role for EURATOM, passing the data of EURATOM inspections to the IAEA, but this met by French opposition because the Republic of France was not part of the NPT but was the most inspected EURATOM state. The final negotiation took the form of IAEA INFCIRC/193 in September 1973. It provides guarantees to solve the problem. It recognizes the EURATOM safeguard system and avoids overlapping with it where possible.

EURATOM committed to enact subsidiary arrangements with the IAEA and to implement INFCIRC/193. With Regulation 3227/76 of October 1976, EURATOM outlined the technical aspects to implement safeguards in the new non-proliferation regime. The Commission was charged with gathering the required information necessary to reach subsidiary arrangements between EURATOM and the IAEA. The Regulation provided the legal basis for Particular Safeguards Provisions, which are to a large extend obligations defined by EURATOM and placed on individual operators. These provisions were needed before the agreement on Subsidiary Arrangements between IAEA and EURATOM. The Particular Safeguards Provisions defined by Regulation 3227/76 obliged the operators to provide to EURATOM what then EURATOM needs to supply to the IAEA as obligation agreed in the Facility Attachments (which are part of the Subsidiary Arrangements between IAEA and EURATOM). [13]

The Regulation 3227/76 came after a major turning point in the European history, the first enlargement of the European Communities with the United Kingdom entering in EURATOM. When the deal was drawn up with the IAEA, the United Kingdom was already a member of the European community, as it formally joined it from 1 January 1973.

The British nuclear complex was co-processing the nuclear materials designated for defence and civilian use. They did not have a physical distinction between the two tracks in some nuclear facilities.

The UK-EURATOM-IAEA verification Agreement of August 1978 was a “voluntary offer” of the UK Government to put safeguards on some nuclear facilities because they host nuclear materials transferred to the United Kingdom based on bilateral agreements subjected to safeguards.

Conclusions

The historical relevance of EURATOM in the safeguard realm is twofold. First, the EURATOM safeguards system substituted the American cooperation agreement: as we saw, the EURATOM safeguards were the only European assurances in the US-EURATOM agreement for transferring nuclear technology and materials

framework that the Americans received. The EURATOM safeguards disrupted the usual model of verification by being the first time a receiver is not monitored by the provider, rather the receiver monitors itself.

Second, the neighbour-check-neighbour principle implemented by the EURATOM safeguards was not overpowered by the IAEA safeguards and EURATOM kept its right of self-inspection. In the IAEA safeguard system, the inspectors came from a multitude of countries. Members of the same agency often had conflict among them. In the EURATOM safeguard system, the inspectors only came from members of a regional Community with stronger ties than the IAEA. The EURATOM commission shall only satisfy itself, not other authority above it. Because ultimately it shared the same priorities of the IAEA on avoiding military diversion from civilian uses, it was possible to reach a deal.

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The Basic Principles of Nuclear Material Management

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Abstract

This lecture will introduce the students to material management principles and in particular what is different about nuclear material management. The focus will be on nuclear material control and accountancy and the impact on process operations and engineering and construction design. It will describe the components of a Nuclear Materials Accountancy (NMA) and control system and the underlying aspects of mass balance accountancy and independent verification by safeguards agencies. The lecture will include practical implementation issues and operational issues across the nuclear fuel cycle.

Introduction

This paper presents my own personal views on nuclear material management and nuclear safeguards within the area where I am most experienced – large scale plants handling nuclear materials in a wide variety of bulk forms (liquid, powder, metal, gas, etc).

My background is (over 30 years) in nuclear material management working for British Nuclear Fuels, historically a major provider of fuel cycle services based in the UK.

During my time at BNFL I was a System Designer for nuclear material accountancy and control systems, a Master Production Scheduler for plant operations and the demand/supply chain, the Senior Nuclear Material Accountant for the large uranium conversion and fuel fabrication facility at Springfields, the Senior Nuclear Material Accountant in the large plutonium, MOX and waste facilities at Sellafield, and finally I was the BNFL Head of International Safeguards with responsibility for policy and standards for nuclear material accountancy and for interfacing with the safeguards authorities. Since leaving BNFL in April 2007 I have worked as an independent consultant on NMA and safeguards.

The Origins of Material Management

The oldest known writing (some 3200 BC) took the form of a material account. A set of tokens found in an Egyptian tomb recorded an account of linen and oil, documenting quantities and origin. Egyptian bookkeepers kept meticulous records, checked by elaborate audit.

The need to record materials grew as it became important for measuring wealth, for trade and for logistics during the wars that have ensued over the centuries.

The real surge in managing materials came with the appearance of money and arithmetic. Ownership, personal wealth, commerce, investments, taxes and credit all flourished as a consequence and set the key conditions for the development of double entry bookkeeping in Fourteenth Century Italy by Luca Pacioli. Luca set out guidelines for inventory taking, for timeliness of accounts to view customer assets and liabilities and for the running book concept. Accountancy formed the basis on which modern business would grow, flourish and respond to owners, suppliers and customers. It formed the basis on which nations would organise the logistics of wars and exploration and it formed the evidential base for meeting the growing burden of regulations and laws which emerged.

The Business Model for Materials Management

Modern manufacturing and processing businesses have a common business model, which incorporates:

- the financial state of the business, its assets, its unit costs, its storage costs and its profitability;
- the commercial state of the business contracts with customers, delivery and order requirements;
- the purchasing and receipt of goods, components and raw materials with the logistics of managing the warehouse arrangements;
- the manufacturing process, bill of materials, work schedules, product design, process efficiencies, assembly, disassembly, item tracking, build and quality assurance.

The core elements of procurement, production, storage and supply distribution has led to the creation of a software package solution. At first these packages were often known as Materials Requirements Planning (MRP) packages which later became Materials Resource Planning (MRP2) as they incorporated other resource elements such as manpower. The inclusion of broader financial human resource elements has formed complete Enterprise Solutions. The most common of these is the SAP software package. SAP is adopted by many companies, including nuclear companies.

The Lure of a Commercial Package

For large companies, an enterprise wide business solution is an all-encompassing approach to business which aims to remove duplication in a broader sense. Senior managers are particularly attracted to such package solutions because they: -

- have known costs;
- are immediately available and usable;
- have known and proven functionality;
- are reliable and supported;
- have wide user coverage.

The perennial question asked by senior managers, unfamiliar with nuclear material management, is therefore *"why can't we control, manage and account for our nuclear materials using a commercial business software package?"*

Anyone who looks at this issue will see synergies but could and should nuclear material management be done by such a business package? Ask any consultant, and you will be told that the commercial business package can do anything given resources to write bespoke code, ingenuity in using the package and users prepared to accept a less tailored solution.

Nuclear material management is not a proven feature of these packages and much glue is required to piece together those parts of the package, which would collectively form the management of nuclear materials. Companies such as EDF and Urenco have taken the SAP enterprise solution and have incorporated bespoke add on elements for their relatively simple nuclear accountancy and safeguards reporting needs.

There are real differentiators for nuclear material management

Nuclear activities have very significant differences from the standard manufacturing business model.

The nuclear fuel cycle exists in the political world of non-proliferation norms aimed at preventing the spread of nuclear weapons. Safeguards verification, physical protection and trade controls all aim to control access to nuclear materials and sensitive technology.

The nuclear fuel cycle also exists in the shadow of the health and safety risks of ionising radiation and the considerable radio-toxicity risk from ingesting nuclear materials such as plutonium. Safety considerations require the facility to err on caution, to monitor nuclear safety using failsafe systems, independent of all other systems.

No other materials management has to meet the demands of criticality control with its inherent complexity dependent on material form, geometry, isotopic composition, and element mass values. This is further complicated by the changing nature of nuclear materials due to nuclear decay and transformation and requires unique nuclear data on reactor burn up, cooling times, radiation activity etc.

The potential risks of nuclear materials and the associated complexities of fuel cycle facilities has led to a prescriptive regulatory and licensing environment accompanied by close stakeholder scrutiny and subject to significant public debate. The fuel cycle is subject to direct and independent verification by inspections with wide ranging powers of access and high traceability requirements which demand high transparency of operations and records.

All these factors are significant in bulk handling facilities and are acute and intrusive in bulk handling facilities which handle sensitive nuclear materials such as separated plutonium and highly enriched uranium.

The web of stakeholders with an interest in the nuclear industry is wide ranging both nationally and internationally and the industry is watched by the media and the anti and pro-nuclear lobbies. The nuclear license to operate relies on strong assurances that the nuclear fuel cycle is safe, secure and safeguarded. This requires technical assessment of a wide range of nuclear data and demands a very high level of data and systems integrity, especially for plutonium. My own assessment is that the enterprise solution type of package has still not arrived yet for large bulk processing plant needs.

Safeguards, Security and Safety

Safeguards security and safety are underpinned by the control of nuclear materials and operations. Because of this commonality I often find that even people experienced in the nuclear fuel cycle and its technology have problems differentiating between these functions.

The difference is most obvious when we consider the motives and goals of each of these functions.

Safeguards is intrinsically concerned with Treaty compliance, a confirmation that a state is not pursuing or helping other states pursue nuclear weapons. Security on the other hand is to protect sensitive property, information and nuclear materials and to be able to recover nuclear materials in the event of a security breach. Safety is concerned in the wellbeing of people and environment and to protect them from radiological harm and to prevent accidents or injuries.

The confusion arises at the shop floor level where the measures applied have strong synergies, overlap and common techniques. All are concerned with containment to control access, all are concerned that material does not get diverted into areas of plant where it should not be, all use monitoring and surveillance techniques especially gamma and neutron monitoring, all employ some level of verification and assessment and all have qualitative criteria. What is acknowledged by all is that an incident in one sphere is quite often an incident in the others. A loss of nuclear material for example is quite clearly of a safeguards, security and safety concern. A loss in material control is a likewise common concern. The fundamental difference is that

security and safety are protective and preventative measures and so are pro-active. Safeguards however is a historical verification in order to detect anomalies and therefore is a lagging and re-active measure. This distinction is also highlighted in the fact that safeguards is an international competence whilst safety and security are national competencies.

Safety and Security Influences on Nuclear Material Management and Safeguards

Nuclear plants have always had massive construction for seismic protection and for radiation protection but as plant radiological protection has increased and dose limits have tightened, then access to nuclear material has become increasingly difficult. Complete access to nuclear material for independent verification is therefore at odds with the dose reduction led move to automation and remote operation and risk led move to minimise handling. This is particularly so in the most hazardous operations which accompany decommissioning or servicing old facilities. Nuclear safety is paramount and the safety culture tends to create a conservative and pessimistic approach, which increasingly impacts on safeguards.

Likewise, the events of 9/11 and the ongoing terrorist threat have heightened security arrangements with consequent impact on access to plants, materials and information. Reports and data in all its forms (documents, pictures, drawings etc) are subject to security classifications and disclosure difficulties again a feature at odds with the need for openness, transparency and full information required by safeguards and more recently by the safeguards additional protocol reporting. For example security is at its most vulnerable during transport and therefore any advance information on what, where and when transports will take place must be protected.

Information security management however has some relevance to safeguards reporting which calls for records to be trustworthy and provide assurance of record authenticity and availability.

Safeguards, Security and Safety Underpinning by Material Control

In order to manage materials effectively it is necessary to have proper material control. This requires that a facility can locate all its nuclear materials and properly record and track what is happening with those materials so that it can be fully accountable for all its nuclear items, work in progress, wastes and effluents. To do this it must be able to do two things. Firstly, to have objective data in the form of nuclear material masses based on good measurement. Secondly to ensure that what it thinks it knows is in agreement with reality. Like a supermarket it is not sufficient to control its inventory by assuming what it thinks is on the shelves is in fact on the shelves. This requires that there is capability and access to conduct a physical verification, a stock check, a Physical Inventory Taking (PIT).

Material Control Sub Processes

Attached in Appendix one is a table containing a variety of the sub processes which make up the overall process of material control. If we take some examples from that table; container control, seal control, and segregation of materials we can see that these are fundamental to the physical verification process and efficient and effective operations. If there is inefficient and ineffective control, then this will certainly manifest itself in poor nuclear material accountability.

Material Control Areas

The basis of good material control is to be able to exercise control in a manageable and meaningful way. It is obvious for large bulk handling facilities like those at Sellafield and La Hague that is only manageable if the sites' facilities are broken down into more specific plant level control areas.

The physical boundaries of each control area should be unambiguous and the point of transfer and hand-over arrangements for custody for nuclear materials leaving or entering the area should be well defined. This ensures that there are no split accountabilities and there can be a clear focus on who is responsible for control.

The choice of material control area boundaries should be such as to maximise control of material flows. This requires good measurements on the flows and an ability to carry out inventory taking of the materials held in the control area.

These control areas should also be drawn up in such a way as to underpin the safeguards concept of Material Balance Areas (MBAs). Running balances of nuclear material should be available for each control area. Why not just utilise only the safeguards MBA structure? These can be very large for example a fuel fabrication plant may be one MBA whereas from a management point of view that scope is too big for focusing responsibilities and accountabilities.

Assign Material Custodians

At all nuclear facilities there are a range of people who impact on the nuclear material management process; from people on the plant, through to designers, IT specialists, commercial functions and material accountants.

Two key groups of people within this population are the operators who actually have custody of the nuclear material (the material custodians) and the nuclear material accountants who keep the records of the nuclear material.

Each material control area should have a single material custodian appointed and that person should have direct control over material within their own plant area and be responsible for:

- procedures, instructions and records;
- conduct of regular stock checks;
- measurement quality;
- materials segregation and labelling;
- monitoring and notifying plant modifications which affect control;
- investigating control discrepancies;
- training and educational needs of personnel within their area;
- continuous improvement;
- representative and repeatable sampling.

Measurement Quality Control

All measurement, sampling and analytical techniques need to be subject to measurement quality control. This ensures that measurement performance is technically defensible and in line with the prevailing national and international standards. A programme for controlling measurements includes the procedures and activities

used to ensure that a measurement process generates measurements of sufficient quality for their intended purpose.

Measurement quality requires precision and accuracy data for mass and isotopic measurements, sampling and analytical methods. Using these data, it is then possible via statistical analysis to determine whether the mass balance performance is within what can be expected from measurement uncertainties.

Measurement errors are unavoidable in large bulk handling facilities. The measurement challenge is considerable for example on large tanks containing many tonnes of highly active, hot, circulating dissolver liquors with a low concentration of plutonium in acid. It is also normal to have random error variation between one measurement and another and in some cases it may be that the measurement is subject to some underlying bias which gives rise to systematic errors.

It is easy to say that systematic errors and biases must be identified and removed but there may be prohibitive radiological, technical and financial reasons why this is not possible. In such circumstances it is considered permissible to adjust the measurements for the systematic error where there is a defensible, documented and accepted assessment of the error.

The Hold-Up Challenge

Protagonists of the nuclear industry suggest that bulk handling plants are awash with nuclear material such that they cannot be adequately safeguarded and that material 'stuck in the plant' could conceal clandestine diversion of nuclear material.

For this reason, it is necessary that the plant must be capable of minimising the amount of material in difficult to measure parts of the process at stock takes. This is done either by complete clean out, or if that is impracticable, by an empty down to a level where the uncertainty is acceptable or to use in process hold up estimates derived and validated during commissioning or estimates derived from validated computer modelling.

The most difficult hold-up is the hidden inventory which deposits/collects on surfaces (of glove boxes, pipes, equipment etc) and is generally “lost” to the fabric of the plant until there are considerable dismantling and cleaning operations. Decommissioning is such an exercise and it is common during decommissioning to “find” nuclear material deposits in the fabric of the plant. These deposits generally appeared as apparent “losses” of nuclear material in the plant during its operational lifetime, especially during start up.

Operators have gone to considerable efforts to deploy effective systems and modes of operation to avoid hold-up. This includes systems which keep the material in the locations it is meant to be in. It is common for equipment to be interlock connected and to form the primary containment layer. That containment layer is usually then supported by breach detection and response systems that either collect the nuclear material or keep it in place.

The hold-up aspect of nuclear material control has the potential to completely stop plant operations. In the case of the MOX fuel fabrication plant at Tokai Mura, a difficulty with hold up in the 90’s resulted in the shutdown of the facility for over 2 years and over $100m was spent to recover the material from glove box surfaces.

Nuclear Material Accountancy (NMA)

The basic aim of NMA is to know how much nuclear material you hold, in what form, where it is located and how is it contained.

Notwithstanding the needs of international safeguards, the plant operators have an obligation under governance and due diligence to control, protect and account for all nuclear material in their care. This stems from customer, regulatory and public acceptability requirements.

From a practical perspective, it is also necessary for a business to account for its nuclear materials in order to manage its resources effectively, ensure product quality and integrity and for the logistics of planning plant operations.

It should be noted however that NMA, whilst being of key significance, is one of a number of integrated measures employed by the operator to carry out material management.

The Underlying Pillars of NMA

The fundamentals of NMA are that all events and transactions are recorded and that the system of material identifiers and recording allows a full batch tracking capability so that stocks can be derived. All these data have to be resolved into their elemental mass units and all the inventory items must be checked regularly against the physical reality. With these data accounted for, it is then possible to maintain a running mass balance for a given account and to show a permanent state of reconciliation between accounts by using a double entry bookkeeping system.

There will however be reasons why an account balance may differ from the physical inventory found during a stock take. Inventory difference is commonly referred to as Material Unaccounted For (MUF). Other difference may also explain balance anomalies, for example when what a shipper sent wasn't what came out of the process. Shipper Receiver Differences (SRD) are common and represents the difference between the shipper's and receiver's measurement capability. In the case of reprocessing this represents the inherent uncertainty of plutonium content of spent fuel as derived from reactor calculations.

What do material accounts look like?

A material account in many respects is like a money account. In financial accounts all transactions are resolved into money terms, similarly in NMA all transactions are resolved in nuclear masses (uranium, plutonium, thorium etc.). Most people have a bank account and would expect that for their account they will receive statements which show their opening balance, their transactions in and out, any interest or charges and finally their closing balance. They would expect the closing balance of one statement to match the opening balance of the next and would expect that where they transfer between several accounts that they could see the issue from one account exactly mirrored as a receipt in another. If like me, you use internet banking then you have come to expect that you can look at your current balance quickly and anytime on demand. You might also expect that you can call up your transactions and look more closely at the details. Yes, it's that simple just substitute masses for money and MUF for charges/interest and the analogy is complete. The important difference of course is that money does not have a measurement uncertainty and a balance error is fundamentally a mistake.

An account need not be just for a customer statement of nuclear material it can be constructed for whatever a operator needs. In safeguards, the inventory change report is essentially an account at the MBA level.

Custodians would expect an account at the plant control level. Planners might expect accounts of given material forms. A double entry material account system would then simply look as follows:

Account X			
Opening Stock	**100**		
Receipt from Y.	**50**	**Issues to Z**	**75**
		Issue to MUF	**10**
		Book Balance	**65**
Totals	**150**		**150**

Account Y			
Opening Stock	**500**		
Receipt from B	**60**	Issues to X.	**50**
		Issue to A	**20**
		Book Balance	**490**
Totals	**560**		**560**

The modern norm is for nuclear material accounts to maintain a running book with a mass balance available at any time. For item areas, in addition to the mass balance, the inventory can be listed by batch and by locations. Data capture is automated in that data are transferred from process distributed control systems rather than via forms. The traceability features will allow full visibility of the history of a batch including any corrections made.

Generally Accepted Accounting Principles (GAPP)

NMA has no international standards but in general follows many of the principles used in financial accountancy (GAAP). The appropriate principles for NMA are given in Appendix Two together with an NMA interpretation and illustration of the principles.

For safeguards detection of diversion perhaps there are more specifically stated principles consistency, completeness and timeliness of data capture and accountancy recording. These are all required for inspectors to have transparency of operations, certainty of authenticity and something to compare their own measurements against. With these then inspectors can draw safeguards conclusions and give the safeguards assurance of non-diversion.

Checking the Physical Reality

The quantity of nuclear materials held in a control area at a given point in time is known as the control area's physical inventory. The Physical Inventory Taking (PIT) involves checking the reality of what is physically present.

If the control area is a production process, then a number of special arrangements are involved. These include activities to orchestrate the inventory to achieve its most accurate state for checking against the accountancy books. This usually entails emptying and cleaning the plant vessels and glove boxes but may also be achieved

by converting the in-process nuclear materials into a measurable form or transferring them into vessels where they can be accurately measured.

In order to synchronise the inventory taking it is necessary to hold the inventory constant until all parts of the control area have been recorded. This often makes it necessary to suspend all nuclear material movements. The inventory result is not immediately known as it often has to undergo calculations to convert liquid volumes into uranium and plutonium masses and to await analytical results taken at the time of inventory. All instruments used for nuclear materials measurements at the PIT must be in calibration and have calibration and measurement uncertainties data available.

It is important to stress that this is a real physical activity and the inventory should not be determined simply by calculating the difference of receipts and issues in a particular vessel or from taking down positions from tag boards in plant offices. Where health and safety considerations prevent the taking of a 100% inventory then the PIT resorts to the use of an approved sampling plan. In order to avoid confusion, it is necessary to know where containers and locations are empty and/or contain other than nuclear materials. This requires a degree of marshalling and segregation.

PIT is an expensive exercise and normally takes out at least a week from the control areas operational schedule. Many control areas are interconnected and an inventory anomaly in one control area may appear in another. Therefore, where control areas are part of the same flow sheet (reprocessing, fuel fabrication, uranium conversion etc) then these must be done collectively for the same point in time.

Some operators stop all areas and conduct a single large annual inventory whilst others utilise natural plant outages to conduct PITS.

Inventory Difference

Quite simply, this is the difference between the physical reality and the accountancy books. In order to bring the books into line with the physical reality it is necessary to record book losses or gains known as Material Unaccounted For (MUF). In an ideal world with no mistakes and normal operation then the MUF value should fall within the range justified by measurement errors on the flow throughout the year and on the PIT itself.

In order to judge from accountancy whether the plant is being effectively controlled it is necessary to assess the significance of the MUF. A process of error propagation and statistical testing can identify whether the MUF is significant, which measurement points are the biggest contributors and where improvements should be directed.

MUF Susceptibility

The quality of the material balance is determined by the completeness and correctness of the control area's flow and inventory information. The accuracy of such information is most susceptible to:

(a) The uncertainty on:

- the nuclear material held as work in progress in the process;
- the hidden inventory which is lost to the fabric of the process;
- residues for recovery, especially those which are heterogeneous.

(b) The adequacy of the:

- measuring equipment at boundary or key measurement points;

- representative and repeatable sampling;
- constants or estimates used for nuclear material quantification.

(c) The effectiveness of internal controls:

- to detect and correct biases, detecting mistakes, abnormal conditions and trends;
- to determine the completeness and correctness of both the flow and inventory information;
- maintain data authenticity, especially during any manipulation, processing or manual intervention;
- synchronise important events in order to present a physical/ book reality for a fixed point in time.

The other checks and balances fundamental to accountancy performance are those that relate to the bulk weight balance, the item balance, and to a lesser degree, the isotopic weight balances. Each of these will have susceptibilities.

MUF is published in the UK, the US and Japan and needs to be seen in the context of the historic and cumulative MUF positions, the significance against throughput (and therefore measurement uncertainty) and the assurances from the safeguards, security and safety arena. However, the figures are presented, the media headlines will always be theatrical for any apparent MUF loss of plutonium.

NMA Versus Material Control

NMA is a lagging indicator of accountancy performance in that it is always retrospective by nature of record historical information. It can tell the operator that MUF investigations are required but only once a year. In that sense NMA is reactive. On the other hand, nuclear material control is a leading indicator of what will be the accountancy performance and its preventative nature means that material control is pro-active.

There is however a half-way house between control and accountancy - a system known as Near Real Time Accountancy (NRTA). For MUF to be a proactive control tool it must be timelier and more frequent. A sequence of MUF data would then be available for a control area rather than only at PIT time. This can be achieved by frequent intermediary inventory estimates during plant operation. Such inventories suffer from higher uncertainties but allow statistical analysis to detect an abrupt or protect MUF event.

Safeguards Obligations and Objectives

An ancient Greek quote sums up the modus operandi of the safeguards verification regime to date, "there is only one safeguard known generally to the wise – suspicion".

From my dealings with the detailed implementation of safeguards, a suspicions approach coupled with highly automated facilities has led to significant complexity in safeguards approaches. A comprehensive and all-embracing safeguards approach is increasingly costly and in sensitive bulk handling plants requires significant capital investment by the operator on NMA and by the inspectorate on installing in line independent monitoring equipment. The costs don't stop there, since frequent inspections carry a large manpower cost and an ongoing impact on operations.

The objectives of safeguards are simple. The aim is to be able to detect a loss of a significant amount of nuclear material in a reasonably short detection time. Verification seeks out inconsistencies in the accountancy, the measurements or the plant layout.

The Safeguards System is a Function of:

The efficient and effective functioning of safeguards at an installation and hence, the quality of the safeguards system is a function of the following:

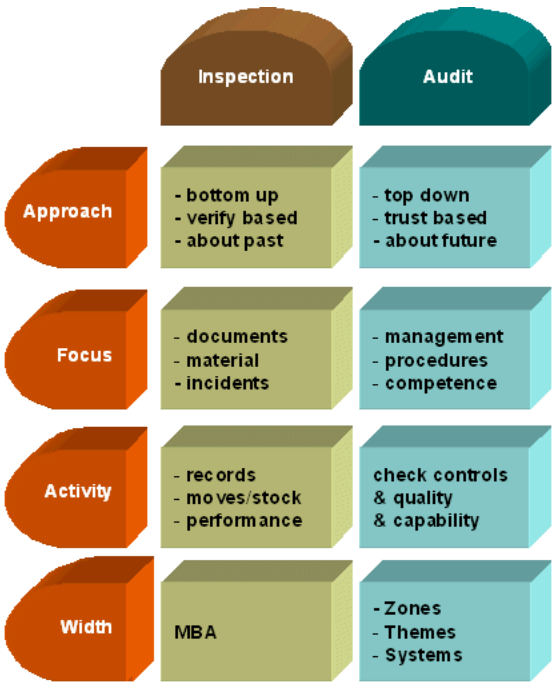
- the quality of the safeguards reporting (the degree to which the installation processes satisfy the specific requirements);
- the inherent level of NMA and safeguards provision in a new plant or major modification;
- the degree of ease that the Commission can independently verify the nuclear material and the bookkeeping;
- the degree of confidence provided by the presence of safeguards in depth features which avoid over-reliance on NMAC for drawing safeguards conclusions; and
- the noise on the material balance (the level of mistakes and timeliness).

Safeguards Verification and Audit

Non-proliferation safeguards has been based on the principles of independent verification and universality. The European Commission has complemented verification with a broader system of audit. Procedural audits and inspection verifications can both check effective compliance; both can check the NMA completeness and correctness.

Audit used in the form of continuous improvement is about improving the future, whereas inspection objectives are fundamentally about checking the present in order to confirm history. The detection capability is very different in an auditing perspective. The system must now give assurance that no substantial loss can occur undetected by the operator. That implies a system where operators and inspectors must be complementary and therefore a certain level of trust must therefore be awarded to the operator.

Whether audit or inspection, the question remains “are safeguards measures a burden and are they too intrusive?” For large bulk handling facilities processing plutonium the burden is significant:



(a) The level of independent safeguards equipment installed in the process:
    1. Cameras
    2. seals to prevent tampering or access
        a. cameras and detectors
        b. panels and cubicles
        c. junction boxes
        d. ventilation ducts
        e. doors
        f. Maintenance access points
    3. motion detectors
    4. neutron and gamma monitors
        a. spent fuel
        b. reprocessing hulls
        c. PuO_2 cans
        d. MOX pellet trays
        e. MOX pins, active length
        f. MOX fuel collars
    5. bar-code readers.

(b) There are numerous points where the safeguards authorities utilise the operators own equipment using signal branching.

(c) There is a level of sample taking sufficient to support a fully equipped on-site safeguards authorities owned laboratory.

(d) There is frequent inspection (at least monthly) and with large sites a virtual continuous presence often requiring the inspectors to have their own dedicated accommodation on site.

(e) Safeguards inspectors have their own IT network, data transmission, and remote monitoring arrangements.

(f) There are frequent and substantive requests for detailed plant operation and forward programmes.
    1. For surveillance
        a. Plant/glovebox layout
        b. Mechanical equipment
        c. Access points and building penetrations
        d. Normal plant flows

(g) There is an ongoing process of verification/re-verification of the plant design:
    1. Sampling lines/treatment
    2. Plant modifications
    3. Declared vessel capacities
    4. Calibration/homogenisation systems
    5. Pipeline and cable runs
    6. Process models
    7. Recycle and waste routes
    8. Penetrations
    9. Key measurement points.

Most large scale bulk handling plant operators would say the answer on the questions of safeguards intrusiveness is that this is the price to pay for operational acceptance. The inspectors however have a duty to avoid impacting on production throughput and on product quality.

C/S in a Plutonium Store

Protagonists of the nuclear industry suggest that the current level of separated plutonium in stores present a significant non-proliferation risk. Modern plutonium stores have significant investments which include:

- Massive walls to form the containment and survive seismic events and direct impacts from aeroplanes
- Bank vault style doors with special interlock systems
- Monitors and detectors on the flow routes in and out
- Complex multiple containment package which forms the plutonium can
- Camera surveillance at all times with uninterruptable power supplies
- Double and often triple levels of containment and surveillance with redundancy
- Remote operation and man access only for breakdown and infrequent maintenance
- Identity readers, NDA monitoring and weighing for the cans
- Secured channels holding the cans
- In situ verification of cans using probes
- Security access constraints which include the “two-man rule” and secure grills on penetrations.

In this case it is hard to see how the risk from one can of plutonium, one hundred cans or 1,000 cans differs. The measures are the same, irrespective of the content.

Bulk Facilities

It is important to summarise and conclude on some key points concerning bulk handling facilities:

- A high standard of measurements is only necessary in bulk handling installations, where high measurement accuracy contributes to achieving acceptable MUF and SRD;
- The operator’s accountancy systems cannot be expected to detect the removal of a small quantity of material from large processes or provide a fast enough response to be useful in helping prevent theft or diversion;
- Bulk facilities have lots of feed, intermediate and product materials where the container acts as an item. The loss of an item is always significant and a serious material control, security and safety issue;
- For large scale reprocessing plants of around 1,000 tonnes of heavy metal the uncertainty of measurements exceeds the detection goal quantity of 8kg plutonium. A measurement uncertainty of 0.1% is extremely hard to achieve but even at this level some 30Kgs plutonium MUF is possible within the measurement uncertainty.
- The IAEA forum, LASCAR (Large Scale Reprocessing) concluded that to gain high-level assurance in such plants a wide range of techniques are necessary. Such a network of independent measures is referred to as “safeguards in depth” and includes qualitative factors based around comprehensive knowledge and observation of the plant.

Safeguards Provision in New Build

Europe is now making provision for new reactor build. The public debate that surrounds new build is concerned with the fuel cycle aspects and what to do with the spent fuel and particularly the nuclear waste. There is no doubt the role that nuclear fuel cycle non-proliferation assurance plays has a direct bearing on new build. A stable NMA and safeguards performance across nuclear fuel cycle facilities is an enabler to new build acceptance.

My experience is that operators see the need for non-proliferation assurance and support the aims and objectives of the safeguards authorities. New build and the impact on nuclear fuel cycle services need to include safeguards considerations at the outset. Involving the safeguards authorities early in the design process ensures adequate provisions for safeguards and proper NMA underpinning.

Safeguards and NMA for Nuclear Liabilities

Europe is also shutting down reactors and decommissioning old facilities. These scenarios often involve contractors unfamiliar with NMA and safeguards and operators must continue to ensure adequate recording of plutonium and uranium continues into the waste management and recycle environment including final disposal or return of wastes to owners.

Conclusions

Nuclear material management has unique features which make it different from normal material management systems. The difference is that nuclear material management is more demanding and more constrained.

It is important to recognise that whilst safeguards, security and safety are different they do have material control in common. Material control also enables NMA, (recognised in the IAEA model safeguards agreement as of “fundamental importance”).

Safeguards and NMA are at their most technically complex in bulk handling facilities. In those plant which handle sensitive nuclear materials safeguards are intrusive on operations and at their most costly to both facility operators and the safeguards inspectorates.

In the final analysis, the nuclear industry, like safeguards, is driven by politics. We need to harness the full range of systems to enable strong assurances to be drawn that the industry is safe, secure and safeguarded.

Acknowledgement

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Appendix One – Material Control Sub Processes

Material Control sub processes	
• Location management	• Process Efficiency (bulk) Monitoring
• Containment and container control	• Statistical process control
• Access/use control	• Enrichment control/monitoring
• Identification/labelling	• Release of analytical results for application
• Verification/confirmation of receipts	• Quality Control
• Traceability and tracking	• Investigate differences (MUF/SRD)
• Item control	• Seal control
• Transfer controls	• Control of material hold-up/cleaning
• Change controls	• Segregation of materials
• Check inventory record accuracy	• Control of wastes/residue arising
• Control Data timeliness, quality, authenticity	• Controlling manual overrides

NMA concerns itself with items and amounts of nuclear material, whereas operators control nuclear material for at least five distinct reasons:

- Operational - to meet operational objectives;
- Physical Security - to prevent theft/misuse;
- Radiation Safety - to protect staff/public;
- Criticality - to prevent unplanned radiation excursions;
- Accountancy - to satisfy international, national and local regulations.

Safeguards is not directly concerned with the first four of these.

Appendix Two – Generally Accepted Accounting Principles (GAAP)

All NMA systems must be based around fundamental aspects of accountability often founded on principles from the financial arena:

Double entry bookkeeping - Double entry accounting keeps the records in equilibrium thus reflective of reality.

Accounting entity - Define the boundaries of the accounting activity/system.

Accounting period and matching - The accounting & reporting period must be considered when developing and/or operating an NMA system. Matching deals primarily with making the accounting entry in the period in which shipment/receipt occurred so that the comparison of receipts and shipments can be facilitated.

Materiality **-** The need for an accounting entry must be judged against all entries for the period to determine the relative proportion of the single entry with respect to the whole. This principle applies when determining whether to take certain measurements that may be costly, yet will detect only a small amount of nuclear material which may be immaterial when the amount is considered in context to the total MBA. While a single event may be immaterial in itself, if the event is common the total effect of the events may not be immaterial.

Conservatism **-** Because accounting measurements of nuclear materials often take place in a context of uncertainty, estimates or poor measurements are sometimes necessary. This principle requires that in those circumstances these should tend toward a value that is least likely to overstate reality.

Consistency **-** This principle allows for compatibility among successive acts such as accounting entries or measurements as well as comparability of periods and MBAs or installations. All past, present and future acts must be comparable; all should do what they do in the same way. If a change in procedure is necessary, apply the concept of full disclosure.

Full disclosure - This principle requires that all transactions and events be recorded in the accounting records and that all data contained in the records receive adequate disclosure. Any changes in the way measurements or entries are made should be disclosed so that it is known that comparability is not possible without further calculations on the data. Full disclosure is required for all accounting adjustments. This is especially important when inventory differences occur due to re-measurement. Full disclosure requires that NMA knows original values, and new values and what justifies the value change and what assurance is there that the item in question was not subject to a real loss or gain of material.

Objectivity - This is necessary so that those who use NMA reports can have confidence that what they are reading is reality uninfluenced by assumptions, or personal prejudice. Accounting entries and reports must be based on factual data, observable phenomena, and presented factually. For example, never assume what was said to have been shipped (based on verbal assurance) has moved; never deduce correctness by the appropriateness of the container it was shipped in. One should objectively verify what was shipped or received before making an accounting entry.

Continuity - The assumption of uninterrupted succession/ continued existence is necessary to keep records comparable and complete. Any entry or lack of entry into the system will have present and future effects. Failure to apply this principle causes an assumption that an entry or lack thereof will not have an impact. Always assume that operations and accounts are carried forward and will continue.

Measuring unit - The measuring unit must be consistent among individual entries, records, and between control areas, MBAs and installations. Otherwise there can be no comparability, and the probability of confusion and defective decisions is greatly increased.

Substance over form - Not all things are as they appear to be. The receipt of a container marked "Enriched Uranium" should not lead the NMA system to record the receipt of enriched uranium until it is verified that the container does in fact contain the substance. An empty container means that you have uranium in form only, in substance all you have is a container. Another example is when a container is measured and the installation determines that the new value is more precise and thus makes an entry in the NMA system, the difference takes on the form of an MUF. Further evaluation then shows that this item was received from offsite and thus it is not an MUF but rather an SRD. What in form was an MUF is in substance an SRD. Only substance should be entered into the records

Recognising vs realising - This requires differentiation between whether an event occurs and whether the event is recorded. When an event occurs it is said to be realised, but unless the event is recorded it cannot be said to be recognised. It may be that an organisation realises an event took place, but if that event is not recorded/recognised in the records - management, auditors, etc., will legitimately opine that the organisation does not realise the event took place - which is indicative of a lack of adequate control over nuclear materials.

State-Level Safeguards

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1 Introduction

This chapter, structured in three subchapters elaborates on the international nuclear safeguards implementation focusing on the historical State-Level Concept, the State-Level Approaches and the State-Level Safeguards. The first subchapter is dedicated to the history of the implementation of safeguards since the 1960s and its continuous evolution towards a State level focus since the 1970s, the second subchapter describes in detail the rationale behind the international safeguards implementation at the State level and the last subchapter shortly discusses the current status of the State-level Safeguards implementation world-wide.

2 History of Safeguards Implementation at the State Level

The safeguards system of the International Atomic Energy Agency (IAEA) was first implemented in the 1960s to provide exporters of specified nuclear material, technology and facilities assurances that these were used for peaceful purposes only. The system was based on the item-specific safeguards agreements between States and the IAEA (Information Circular INFCIRC/26 type and INFCIRC/66 type agreements). With the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), entering into force in 1970, the overall objective of IAEA safeguards significantly changed as non-nuclear weapon State (NNWS) parties undertook to accept safeguards on all source or special fissionable material in all peaceful nuclear activities within their respective territory, jurisdiction or control, for the purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices. The scope and context of the NPT is therefore State-as-a-whole, but it would take some time for this to be fully reflected in the IAEA safeguards system. Building on the framework of the Comprehensive Safeguards Agreement (CSA - INFCIRC/153(Corr.) type agreements), the IAEA safeguards system has evolved continuously towards a State level focus since the 1970s, with the accumulation of experience, the introduction of new technologies and methods, and the strengthening of implementation through both existing and additional legal protocols. Today the scope of IAEA State-Level Safeguards includes all States, manifested in generic safeguards objectives that depend only upon the type of safeguards agreements in force between the State and the IAEA.

It was realized from the beginning that the IAEA safeguards system must have as high a degree of credibility as possible, and must, therefore, have a clear, attainable objective and a sound technical basis[43]. Accordingly, certain standardized procedures, standards or criteria are required which guide the development of the conceptual basis (*safeguards approaches*[44] and corresponding measures), and the type, frequency and

[43] James A. Larrimore, "IAEA Safeguards Criteria", Journal of Nuclear Materials Management Vol. 21, Issue 3 - 5/01/1993.

[44] For definition of terms, please refer to the "IAEA Safeguards Glossary", or Annex I of "Supplementary Document to the Report on the Conceptualization and Development of Safeguards Implementation at the State Level (GOV/2013/38)", GOV/2014/41.

intensity of the different activities performed (safeguards implementation), against which the results obtained can be assessed (safeguards evaluation) and conclusions drawn.

Elements of such criteria were already established and used in the 1970s as 'evaluation criteria'[45], but it was in the late 1980s that the IAEA placed increasing emphasis on formalizing criteria for use in the evaluation of safeguards implementation for its annual Safeguards Implementation Report (SIR - see subchapter 4 for more information on the SIR and on the data reported in it). In 1988, the IAEA initiated a project to develop and document unified criteria to govern all safeguards implementation and evaluation activities. In January 1991 these criteria went into effect as the *Safeguards Criteria 1991-1995*.

When the Safeguards Criteria were developed, the IAEA, as a way to enhance consistency, had already started to develop and use the so-called *acquisition path analysis* methodology. At that time, the amount of information available to the IAEA about the State as a whole was much more limited than today; therefore, the acquisition path analysis conducted during the development of the Safeguards Criteria was based on the assumption that all necessary facilities for clandestine processing of diverted nuclear material are already in place in the State and tested before diversion takes place. This was a conservative approach: no differentiation could be made between different States in their ability to further process diverted nuclear material. This conservatism was useful, however, in deriving a graded set of requirements introduced into the criteria, which considers the effort (conversion time) with which the nuclear material could be further processed to weapons-usable form.

The criteria distinguished nuclear material in three ways: by category, type, and stratum. Based on the a-priori determined *conversion times* for *significant quantities* (SQ) of nuclear material types, categories of nuclear material were established as *unirradiated direct-use*, *irradiated direct-use* and *indirect-use material*, which were used primarily in specifying *detection probabilities* and *detection times* (timeliness goals). For each facility type and specific inspection activity, the criteria specified, for each nuclear material category and stratum, the required *verification effort*.

2.1. The Integrated Safeguards

Although under CSAs the IAEA has both the right and the obligation to verify both the correctness and completeness of States' declarations, thereby providing credible assurance of the non-diversion of nuclear material from declared activities and of the absence of undeclared nuclear material and activities, for many years its *safeguards activities* were focused primarily on nuclear material and facilities declared by the States. The shortcomings of this limited focus became evident in the early 1990s with the IAEA's inability to detect Iraq's clandestine nuclear weapons programme, and the IAEA together with the Member States therefore recognised the need to expand its focus to the State as a whole. These developments triggered efforts to strengthen the IAEA's ability to exercise its right and obligation to ensure that safeguards are applied on all nuclear material in all peaceful nuclear activities within the territory, jurisdiction, or control of States with a CSA in force.

These efforts resulted in the enhancement of the safeguards system by adding measures giving the IAEA improved capabilities to detect clandestine nuclear activities. These efforts were manifested in an extensive multi-year programme by the IAEA (termed "Programme 93+2", divided into Part I and II), with the strong support of Member States, to improve the effectiveness and efficiency of the safeguards system[46]. The

[45] V.Fortakov, et.al, "Development of Criteria and Computerized Procedures for Safeguards Performance Evaluations", IAEA-SM -293/169, in Nuclear Safeguards Technology, Vol.1. (1986).
[46] Richard Hooper, "The Changing Nature of Safeguards", IAEA Bulletin, Vol, 45-1. June 2003.

objective of Part II was to strengthen the technical and legal basis through which safeguards, while continuing to provide assurance regarding the correctness of States' nuclear material declarations, could better address the completeness of those declarations. These efforts culminated in May 1997 with the Board of Governors' (BoGs) approval of the Model Protocol Additional to the Safeguards Agreements (termed "the Additional Protocol" (AP) and published by the IAEA as INFCIRC/540 (Corr.)).

If under both a CSA and AP, the IAEA, based on the findings of increased efforts required to better understand a State's *nuclear fuel cycle* (NFC), could provide better assurance of the absence of undeclared activities, the result challenged the conservative assumption of the Safeguards Criteria as explained above. This introduced the potential to improve the effectiveness and efficiency of safeguards implementation for those States for which the *broader conclusion* (i.e., both the correctness of declarations and the absence of indications of undeclared activities) had been drawn. Through an optimized combination of *safeguards measures* provided for under both a State's CSA and its AP, and by taking into account State-specific features and characteristics based on the evaluation of all *safeguards-relevant information*, the IAEA sought to enhance the efficiency of safeguards implementation for such States, without compromising effectiveness. The implementation of safeguards in this manner was called '*Integrated Safeguards*'.

In 2001, in the context of Integrated Safeguards, the IAEA began developing individual, customized safeguards approaches for States ('*State-Level Safeguards Approaches*' or SLAs) for which the broader conclusion had been drawn. In an Integrated Safeguards SLA, all plausible acquisition paths by which a State might seek to acquire nuclear material for a nuclear explosive device were covered by safeguards measures. The Integrated Safeguards approach for a State was therefore designed to provide coverage of acquisition paths involving diversion of declared nuclear material from different stages of the NFC, and to address all clandestine routes to the acquisition of weapon-usable nuclear material involving undeclared facilities and/or activities. The design of such an approach included:

a. the consideration of State-specific features and characteristics;
b. the adaptation of model integrated-safeguards approaches for application at specific facilities; and
c. a plan for the implementation of *Complementary Access* at sites and other locations.

The implementation of Integrated Safeguards began in 2003, and by the end of 2013 Integrated Safeguards were implemented in 53 States.

In its SIR for 2004, the IAEA used the term '*State-Level Concept*' (SLC) in reference to safeguards implementation that is based upon *State-Level Safeguards Approaches* developed using safeguards objectives common to all States with CSAs, and taking *State-specific factors* into account. The SLC refers to the general notion of implementing safeguards in a manner that considers a State's nuclear and nuclear-related activities and capabilities as a whole, within the scope of the State's safeguards agreement.

Integrated Safeguards was then the first significant step in the implementation of the SLC, by definition it could only be applied to States with a broader conclusion. However, even for these States the IAEA's verification activities continued to be largely based on a facility-based approach. Differentiation among these States was manifested only in the implementation details of the specific measures to be applied; however, parameters such as the timeliness goals for general categories of material and types of facilities remained independent of the States' technical capabilities, similar to the approach taken by the Safeguards Criteria. As a result, the IAEA's resources remained allocated by a prescriptive approach to activities that could potentially benefit from further State-specific optimization.

2.2 The State Level Concept as a Universal Concept and the State-Level Safeguards

Since the SLC was meant to be a universal concept, in the sense of applicability to all States with safeguards agreements in force, the IAEA continued to evolve its safeguards system based on the experience of the implementation of the Integrated Safeguards SLAs. As a consequence, State-Level Safeguards became the underlying basis for safeguards implementation by the IAEA today. It is applied to all States, deriving *generic safeguards objectives* from their respective safeguards agreements, and taking the rights and obligations of the parties to those safeguards agreements into account. The summary of the scope of application of safeguards agreements and the associated generic safeguards objectives is given in Table 1.

Table 1: Summary of the scope of application of safeguards agreements and the associated generic objectives[47].

Type of agreement	Scope of application of Safeguards Agreements	Generic Safeguards Objectives
CSA (NNWS)	All nuclear material in all peaceful nuclear activities in the State	• To detect any diversion of declared nuclear material at declared facilities or Locations Outside Facilities (LOFs) • To detect any undeclared production or processing of nuclear material at declared facilities or LOFs • To detect any undeclared nuclear material or activities in the State as a whole
Item-specific (Non-NPT)	Specified items subject to safeguards in the State	• To detect any diversion of nuclear material subject to safeguards • To detect any misuse of facilities and other items subject to safeguards
Voluntary Offer Agreement (VOA) (Nuclear Weapon States - NWS)	Nuclear material in selected facilities or parts thereof in the State	• To detect any undeclared withdrawal of nuclear material in selected facilities or parts thereof

In implementing safeguards in a holistic manner, today the IAEA applies standardized processes associated with the planning, conduct, and evaluation of safeguards activities. To ensure consistency and non-discrimination in the implementation of safeguards, the IAEA has enhanced its internal work practices, most importantly the key processes supporting safeguards implementation and the departmental oversight mechanisms relevant to the implementation of these processes. As a result, the implementation of State-Level Safeguards today is a systematized, quality-controlled prioritization and optimization process that is represented by the high-level process illustrated on Figure 1.

[47] Source: GOV/2014/41, "Supplementary Document to the Report on The Conceptualization and Development of Safeguards Implementation at the State Level (GOV/2013/38)", Table 2.

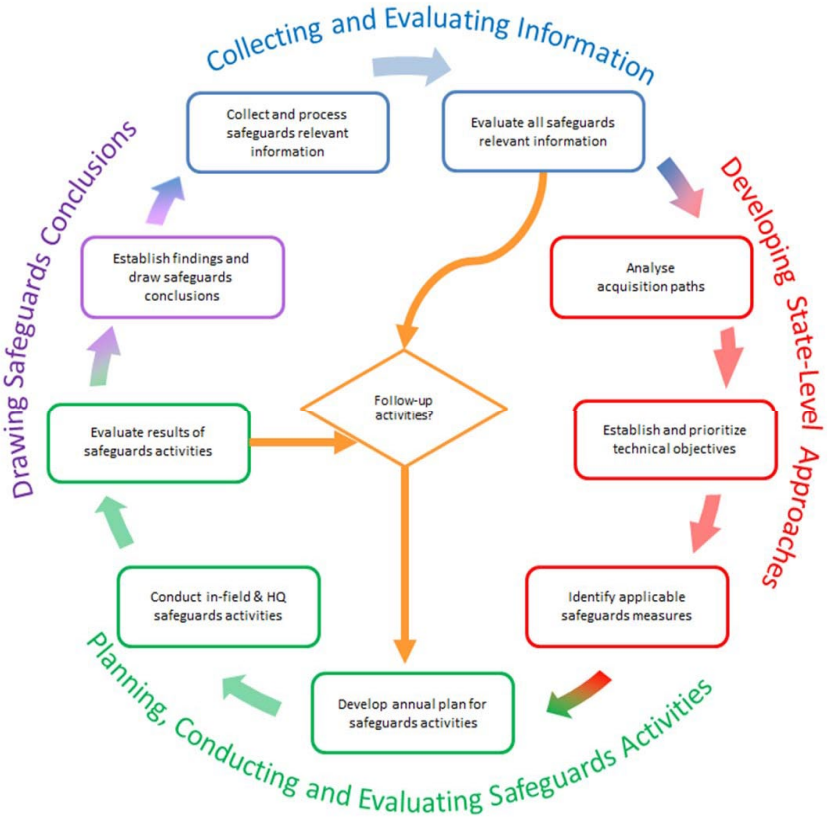

Figure 1: Processes supporting implementation of State-Level Safeguards.

2.3 The State-Level Approach Development Processes

For simplicity, discussion here is focused only on the current status of the SLA development processes, highlighting the key differences as compared with previous safeguards approaches.

In developing and implementing an SLA for a State, and in planning, conducting and evaluating its safeguards activities for that State, the IAEA considers six *State-specific factors* (SSFs)[48]. SSFs are based on factual information about a State, and are objectively assessed by the IAEA in the context of the implementation of safeguards for a State. It can be said that the IAEA, under the current implementation of State-level Safeguards, when developing, implementing or updating the SLAs, makes more systematic use of SSFs than in the Integrated Safeguards SLAs[49]. The influence of the six SSFs on the development steps of an SLA and on the planning, conduct and evaluation of safeguards activities is summarized in Table 2.

[48] For the comprehensive list of SSFs, see Table 6, page 38 of the "Supplementary Document to the Report on The Conceptualization and Development of Safeguards Implementation at the State Level (GOV/2013/38)", GOV/2014/41.
[49] See, for example, the report by the Director General: "Implementation of State-level Safeguards Approaches for States under Integrated Safeguards - Experience Gained and Lessons Learned". GOV/2018/20.

Table 2: The influence of State-specific factors on the steps in the development of an SLA and in the planning, conduct and evaluation of safeguards activities[50].

		State Specific Factors (SSFs)					
		Safeguards agreement and conclusion (SSF-1)	Nuclear fuel cycle and related technical capabilities (SSF-2)	Technical capabilities Of SSAC/RSAC (SSF-3)	Implement certain Safeguards measures (SSF-4)	Nature and scope of Cooperation (SSF-5)	Agency's experience (SSF-6)
Develop State-level Approaches	Analyze diversion/acquisition path	✓	✓				
	Establish and prioritize technical objectives	✓	✓				
	Identify applicable safeguards measures	✓			✓		✓
Planning, Conducting and Evaluating	Develop annual plan for safeguards activities	✓			✓	✓	✓
	Conduct in-field & HQ safeguards activities	✓		✓		✓	✓
	Evaluate results of safeguards activities	✓		✓		✓	✓

To address the generic safeguards objectives for a State, the IAEA establishes State-specific *technical objectives* (TOs) to guide the planning, conduct and evaluation of safeguards activities for that State. The set of TOs, which remain within the scope of the State's safeguards agreement, form the basis for identifying safeguards measures and conducting safeguards activities for a State. They may differ from State to State, depending upon the respective SSFs; for example, the NFC and related technological capabilities of the State (SSF-2).

The TOs are established through the conduct of either an acquisition path analysis (APA - for States with CSAs) or a diversion path analysis (DPA - for States with item-specific safeguards agreements or Voluntary Offer Agreements (VOA)). The implementation of an SLA for a State will focus on attaining the set of TOs established for the State, instead of mechanistically carrying out the facility specific activities listed in the Safeguards Criteria or in the Integrated Safeguards approaches.

The APA is carried out within the IAEA by a *State evaluation group* (SEG), with the support of necessary expertise from the IAEA Department of Safeguards, which makes informed technical assessments about the capability of a State to accomplish an acquisition path. It is therefore essential that the analysis is performed

[50] Source: GOV/2014/41, "Supplementary Document to the Report on The Conceptualization and Development of Safeguards Implementation at the State Level (GOV/2013/38)", Table 6.

in a rigorous, collaborative and consistent manner. Accordingly, the IAEA Department of Safeguards has developed methodologies that guide each SEG in determining:

- the classification of the State's industrial capabilities in relation to NFC stages;
- the technical assessment of the undeclared production and processing of nuclear material at declared facilities/LOFs (hereafter referred to as 'misuse');
- the time assessment of undeclared acquisition path steps and
- the estimation of the total path length

It is clear from the above that the output of the APA process strongly depends upon the State's NFC and related industrial capabilities (SSF-2), it also depends upon the type of safeguards agreement in force for the State and the nature of the safeguards conclusion drawn by the IAEA (SSF-1). Once the APA process is complete, the customized SLA for a State is developed following a standardized methodology as described below.

First, a set of TOs that links the generic safeguards objectives with the results of the APA is established, it serves as a mechanism to enable the planning, conduct and evaluation of safeguards activities for the State. The set ensures that all identified acquisition paths in a State are covered.

To allow for the distribution of *verification efforts* to areas of greater safeguards significance, the TOs are prioritized. The TO priorities depend on the length of the shortest path to which they belong. Shorter paths involving more sensitive materials and NFC stages result in higher priority TOs.

The determination of the level of *verification effort* required to address each TO is based upon the TO's priority, using standardized verification requirements known as *TO performance targets*. The use of performance targets is not a new phenomenon as shown in Table 3. The performance targets under criteria-based and Integrated Safeguards implementation were prescribed implicitly for facility-level safeguards activities based on nuclear material categories and facility types, while under the SLC they are explicitly established at the State level for each TO.

Table 3: The use and the basis of performance targets under the Criteria-based, Integrated Safeguards and State-level approach implementation.

Safeguards Implementation	Performance targets					
	Scope	Description	Basis	Usability for activity planning	Use of SSF	Coverage level
Criteria	All States	Implicit in Safeguards Criteria	NM categories	Prescriptive	INFCIRC/66 or 153 (SSF-1)	High
Integrated Safeguards	CSA/broader conclusion States only	Implicit in IS model facility approaches	NM categories & facility types	Prescriptive	broader conclusion (SSF-1)	Lower*
SLC	All CSA States	Explicit in State Level Approaches	Pathway analysis & TO prioritization	Bounded flexibility	6 SSFs	Lower**

**Relaxed due to the broader conclusion as compared to the Safeguards Criteria*[51]

***May remain the same level as given in the Safeguards Criteria (high) or lowered depending on SSF-1 & SSF-2*

It was already realized even before the introduction of the Safeguards Criteria, that four terms would require quantification for planning implementation and for evaluating safeguards performance: significant quantities, timely detection, risk of early detection and the probability of raising a false alarm[52]. The associated numerical parameters, (i.e. significant quantity (SQ), detection time, detection probability and false alarm probability) would constitute a quantifiable performance target if used together explicitly.

Under the SLC, the TO performance targets for detection of diversion of declared nuclear material at the State level are expressed as detection probabilities for the detection of the diversion of 1 SQ of nuclear material or more within the detection time that is now derived for the corresponding TO from the APA results.

The performance targets for the misuse of declared facilities/LOFs are expressed in terms of selection probabilities (SP) within the *signature time*. SP is defined as the probability of applying a safeguards measure capable of detecting misuse of a facility for the processing of at least 1 SQ of nuclear material, while evidence (i.e. a detectable signature) of misuse is present (i.e. within the signature time). The latter is the maximum time interval available for the detection of the misuse. It is determined during the APA as part of the misuse acquisition step assessment process that considers also whether the signatures are persistent (i.e. detectable after the processing was finished).

Due to the nature of the TOs addressing undeclared nuclear material and activities in the State as a whole (hereafter referred to as 'undeclared'), performance targets cannot be easily quantitatively specified or calculated; rather, ongoing analysis activities at IAEA Headquarters are designed and tailored to the specifics of each State. In addition to these ongoing activities, additional activities relevant to these TOs (Complementary Access, environmental sampling, targeted analysis, trade analysis, etc.) are determined based on the corresponding TOs priorities.

As a next step, safeguards measures and activities, that could be applied to meet each TO, are identified, based on the detectable indicators identified during the relevant acquisition step assessment, and taking the related SSFs into account. To ensure a harmonized approach, the SEGs are provided with standardized lists of TOs, safeguards measures and activities applicable under specific agreements.

In the final phase of the SLA development, the *frequency* and *intensity* of each safeguards activity is established to ensure that the corresponding TO performance target is met. *Frequency* refers to the number of times an activity will be performed in a given year or time period (timeliness goal), and it is based upon the *detection time*. *Intensity* refers to the extent or degree to which the activity is to be conducted. In contrast to the previous facility-based approaches, 'bounded flexibility' is given in the SLA in terms of meeting TO performance targets at the facility-level implementation. *Bounded flexibility* means (i) the ability to select the optimum set of safeguards measures and activities at the facility level, taking all SSFs into account, and (ii) setting their intensity and frequency to meet the corresponding TO performance targets (i.e. as the minimum), subject to the terms of the safeguards Agreement or subsidiary arrangements regarding their frequency (i.e. as the maximum).

[51] For the details of options considered and their comparison, see the report by the Director General: "The Development of Integrated Safeguards", GOV/INF/2000/26.

[52] "IAEA Safeguards: Aims, Limitations, Achievements", IAEA, 1983 (IAEA/SG/INF/4). See also "Report on Safeguards-Related Questions", Memorandum by the Director General, GOV/2107, 19 January 1983.

The IAEA Department of Safeguards established intradepartmental committees to review and evaluate all SLAs and components thereof prior to approval by the Deputy Director General for Safeguards (DDG-SG). The review and approval process for the SLAs is typically iterative, with a duration that depends upon the complexity of the State's NFC and activities.

To date, the IAEA, in addition to updating the SLAs for all States with a CSA and AP plus broader conclusion, has developed SLAs for many other States with a CSA and AP but for which the broader conclusion has yet to be drawn, as well as for a number of States with a CSA but no AP in force, and for one State with a VOA and an AP. The methodologies and the departmental verification requirements referenced above are derived from the experience that the IAEA gained from updating or developing these SLAs. The IAEA continues to develop new SLAs and ensures that a consistent and non-discriminatory implementation of State-Level Safeguards is achieved in all States with the same type of safeguards agreement.

3 Rational Behind the Safeguards Implementation at the State Level

This subchapter discusses more in detail the drivers behind efforts over the last two decades to strengthen the effectiveness and optimize the efficiency of IAEA safeguards at the State level, the rationale (or stated justification) for these efforts to further enhance the international safeguards system, and the legal, policy, and technical guidelines in which these changes are being implemented.

3.1. Extending State-Level Approaches to Comprehensive Safeguards Agreement States not under Integrated Safeguards

In 2003, as part of a budget package that included a major increase in safeguards funding, the Board called for a review of safeguards working methods. As part of this review, the Director General's (DG) Standing Advisory Group on Safeguards Implementation (SAGSI) found that many of the principles underlying SLAs under Integrated Safeguards could and should be applied to states without the broader conclusion. SAGSI's review, which was published in 2004, found that a "State Level Approach should be utilized by the IAEA for all States – not only in the State evaluation process but also in the determination of the nature, scope and intensity of the safeguards measures to be undertaken in a State in a given year."[53] SAGSI's then-chairman John Carlson commented that "Recent experience shows that in making adjustments for State-specific factors the safeguards system must be capable of increasing, as well as reducing, safeguards intensity."[54]

In the 2004 SIR, the Secretariat first reported that the SLC would be extended to include "all the other states with comprehensive safeguards agreements" and that it planned to develop SLAs for all CSA States. In the 2009 SIR, the Agency again reported to Member States that the SLC was applicable to all States with safeguards agreements in force.[55] The DG's 2013 report to the Board stated that the SLC would be applied to all States with a CSA in force, and the 2014 Supplementary Document clarified that the SLC would be applied to all States with safeguards agreements with the IAEA[56, 57]. Since 2014, resolutions of the IAEA

[53] Director General's Report to the Board of Governors. "Reviews of the Safeguards Programme and Criteria." GOV/2004/86, 2 November 2004.
[54] John Carlson: "The safeguards revolution - where to from here?" IAEA Safeguards Symposium, Vienna, 16-20 October 2006, https://www.dfat.gov.au/about-us/publications/Pages/the-safeguards-revolution-where-to-from-here.
[55] SIR for 2009, paragraph 122.
[56] *The Conceptualization and Development of Safeguards Implementation at the State Level*, Report by the Director General, 12 August 2013 (GOV/2013/38) citation to the 2013 SLC Report; *Supplementary Document to the Report on The Conceptualization and Development of Safeguards Implementation at the State Level (GOV/2013/38)*, Report by the Director General, 13 August 2014 (GOV/2014/41).

General Conference have stated that "The SLC is applicable to all States, but strictly within the scope of each individual State's safeguards agreement(s)."

As already discussed in the previous sub-chapter, by 2010, the Safeguards Department had significant experience in developing SLAs for States under Integrated Safeguards, but continued to rely primarily on a prescriptive facility-level approach for in-field verification activities, based on implementation of the Safeguards Criteria for CSA States without the broader conclusion, and modified criteria-based SLAs (a collection of model Integrated Safeguards approaches for different facility types) for States under Integrated Safeguards.

3.2. The Main Drivers for the State-Level Concept

In the 2011-2014 period, IAEA officials began making public speeches about the need to *further develop safeguards at the State-Level* to include all States with safeguards agreements. In advocating the requirement for a new framework to more fully implement safeguards at the State level, three main drivers were identified. Namely, it was recognized that it was needed to continue to improve in several areas: 1) detecting undeclared nuclear activities in CSA states without an AP in force; 2) using scarce resources more efficiently to achieve safeguards objectives without compromising effectiveness; and 3) taking full advantage of all relevant safeguards information in its analysis and decision-making processes.

3.2.1. Noncompliance Cases and Need to Detect Undeclared Nuclear Material and Activities

The first driver of the SLC was the recognition that the IAEA needed to strengthen effectiveness of safeguards implementation in detecting undeclared activities, especially in States without a broader conclusion. While revelations of Iraq's clandestine nuclear program in 1991 served as a catalyst for Program 93+2 (described in subchapter 1), subsequent cases of noncompliance cases in Libya, Iran, and Syria involved undeclared nuclear activities that were not initially detected in a timely manner through the Agency's routine safeguards activities.[58] In response to each of these reports from the DG(s), the BoGs found *Libya, Iran, and Syria in non-compliance* with their respective bilateral safeguards agreements and reported these three cases to the UN Security Council in 2004, 2006 and 2011, respectively.

In 2011 a senior IAEA official acknowledged the challenges posed by these non-compliance cases "In a number of cases, we have not spotted activities that raised proliferation concerns." In stressing the need for the Agency to strengthen its effectiveness in detecting undeclared nuclear activities for all States regardless of whether or not they have an AP in force, then-DDG-SG Herman Nackaerts said:

> *"For the growing number of States under integrated safeguards, the State-level approach has already been developed and applied. However, while the theory is in place, in practice the concept has not yet been fully implemented. This now needs to change. We need to fully embrace the State-level concept in practice and drive the process forward."*

During the May 14, 2012 Institute of Nuclear Materials Management (INMM) workshop on "Evolving the IAEA State-Level Concept," held in Charlottesville, Virginia, then-Director of Safeguards Concepts and Planning (SGCP) Jill Cooley, stated:

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[57] The DG's 2013 report on the concept led to some concerns expressed by some Member States, which were addressed in the Supplementary Document that was submitted to the Board. See additional details in: *Laura Rockwood: The IAEA's State-Level Concept and the Law of Unintended Consequences, JOURNAL ARTICLE - Arms Control Today, September, 2014.*

[58] None of these states had an AP in force.

> *"Recent cases of undeclared activities have not been detected by routine inspection activities. Our current safeguards implementation is largely based on an assessment of risk focused on quantities of nuclear material and facility types. It is critical that we develop a new risk assessment framework to identify proliferation concerns and determine the level of safeguards effort required to address them."*

In a 24 September 2012 keynote speech for an American Nuclear Society - INMM conference, then-Director of Safeguards Operations C Nobuhiro Muroya made the distinction between implementing safeguards at declared facilities and detecting undeclared nuclear activities in the State as a whole.

> *"The key challenge currently confronting the Agency is that safeguards implementation has not been as effective as it should be, nor as efficient as it could be. Despite the adoption of measures to strengthen the safeguards system, there have been a number of recent cases where its deficiencies have been exposed. In most of these cases, safeguards were implemented successfully at declared facilities, while undeclared nuclear activities took place unnoticed by the Agency. If we are to move forward successfully; to maintain our capability to provide soundly-based safeguards conclusions, these deficiencies need to be thoroughly and decisively addressed."*

In a 28 May 2013 key note address for an ESARDA workshop in Bruges, Belgium, then-Director of Operations B Neville Whiting stressed that the IAEA needs to improve its ability to detect and deter undeclared nuclear activities in States without an AP in force:

> *"The Agency needs to strengthen its deterrent capability by increasing the chances of non-compliance being detected. If this is where the real proliferation problem lies, then surely this is where the Agency is duty bound to focus its attention rather than expending its limited resources over-verifying States just because they have the Additional Protocol in force, have made extensive declarations and provided detailed information to the Agency about their nuclear programme."*

3.2.2 Growth in IAEA's Responsibilities Outpacing Financial Resources

The second SLC driver involved the mounting strain on safeguards resources and the need to enhance efficiency and productivity. The combination of an increasing safeguards workload without a commensurate increase of budget required the IAEA to focus its efforts on the areas of greatest need. The growing burden included more safeguards agreements and APs coming into force, more material and more facilities under IAEA safeguards, the development of advanced facility types, such as geological repositories, pyro-processing facilities and high temperature reactors (e.g. pebble bed reactors) and other GEN-IV reactors, and specific country issues, without a corresponding increase in resources.

In his prepared remarks for the ESARDA workshop in a May 2013 workshop, Whiting noted the question of how to allocate resources:

> *"Everything we do has an opportunity cost: we cannot afford to waste money on unnecessary activity. [W]e need to better focus safeguards implementation on areas of greatest safeguards significance, apply our resources more thoughtfully, focus more on areas of higher safeguards significance, deploy more flexible work practices and exploit new technological solutions."*

In his July 22, 2014 INMM keynote speech, then-DDG-SG Tero Varjoranta asserted that the Agency's safeguards responsibilities were growing without a commensurate increase in financial resources:

> *"We all want safeguards to be credible and of high quality. In today's challenging economic climate, the demands on Agency safeguards are growing and becoming more complex. Therefore, to cope with the changing nuclear world, the Agency needs to increase its productivity. In other words – the further optimization of IAEA safeguards is essential… As long as the nuclear world continues to change, we have to adapt and change with it. For me it is clear that without further improvements and optimization, we*

> *will find it increasingly difficult to guarantee an effective, reliable and credible safeguards system."*

To support his case, Varjoranta cited the dramatic growth in facilities and material under safeguards, and resources needed for monitoring Iran's compliance with the 2013 Joint Plan of Action (JPOA), and possibly for increased future requirements in Syria and the DPRK. This resource challenge persists as reflected by then-DDG Yukiya Amano's April 2019 speech at the Center for Strategic and International Studies (CSIS) in which he lamented:

> *"An ever-increasing burden is being placed on our nuclear safeguards inspectors and analytical staff. We have responded by doing our best to work as efficiently as possible and find more cost-effective ways of doing things…We will continue to seek efficiency measures, but we are approaching the limits of what is possible given the need to maintain a sufficient number of inspectors in the field."*

The development of SLAs more specifically tailored to each State, taking better advantage of SSFs, enables the IAEA to make better use of its resources by helping the Agency to "avoid conducting more activities than are needed for effective safeguards."[59] As a counterpoint to this focus on efficiency, a 2020 study by U.S. and Russian experts argued that "Safeguards effectiveness must remain paramount. Efforts to reduce costs should not compromise effectiveness."[60]

3.2.3 Increases in Safeguards Relevant Information

The third driver was the expanding availability of safeguards-relevant information. In the last two decades, several factors have resulted in the IAEA having access to more safeguards-relevant information than ever before including: new technologies; advanced information collection and analysis of open sources (e.g. the internet and the worldwide web, access to commercial satellite imagery, analysis of trade information), new techniques (e.g. environmental sampling and remote data transmission); and new legal authorities (e.g. AP declarations and modified Small Quantities Protocols). Taking advantage of access to ever-increasing amounts of information has provided the IAEA with opportunities to strengthen the international safeguards system; but collecting, validating, evaluating the consistency of, disseminating, protecting and archiving all of this data has also proved to be a daunting challenge.

According to former SGCP Director Jill Cooley, the SLC was in part, "Driven by the desire to take full advantage of the increasing amount of safeguards relevant information available and the growing verification workload resulting from the increasing number of nuclear facilities and quantities of nuclear material under safeguards combined with budgetary constraints…"[61]

In order to address this challenge, the IAEA recognized that it needed to create a framework that would allow it to systematically and objectively make good use of all safeguards-relevant information. This effort is now starting to come fruition with the development of customized SLAs with prioritized TOs and performance targets (see subchapter 1 for more details).

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[59] See for example, Massimo Aparo and Therese Renis. "Enhancing Consistency in the Development of State-level Safeguards Approaches." INMM Annual Conference, Baltimore, July 2020.

[60] *The Future of IAEA Safeguards: Rebuilding the Vienna Spirit through Russian-U.S. Expert Dialogue*, November 2020 (https://media.nti.org/documents/The_Future_of_IAEA_Safeguards_final.pdf), p. 13.

[61] Jill N. Cooley. "The Evolution of Safeguards." Consolidated Nuclear Security, Y-12 National Security Complex, Oak Ridge, TN © Springer Nature Switzerland AG 2020 I. Niemeyer et al. (eds.), *Nuclear Non-proliferation and Arms Control Verification.* https://doi.org/10.1007/978-3-030-29537-0_3

3.3 SLC Looks at State as Whole and Tailors Safeguards for Individual States

As stated above, the SLC is the latest phase in efforts to strengthen and modernize IAEA safeguards. It builds on Programme 93+2, the Model AP and Integrated Safeguards.

In his July 2011 keynote speech at the annual conference of the INMM, then-DDG Nackaerts stressed that the SLC:

> "[i]s a *natural continuation of a process that began in the early 1990s* when strengthening measures were agreed through the Programme 93+2 and the subsequent introduction of the Additional Protocol. For the growing number of States under integrated safeguards, the State-level approach has already been developed and applied. We are not changing the fundamental principles underlying the safeguards system."

The SLC maintains many elements from the 2002 Conceptual Framework for Integrated Safeguards, including: 1) ***flexibility*** in implementing safeguards to allow the IAEA to concentrate its resources where they are most needed (e.g., by *reducing the frequency of inspections* for some less sensitive item facilities, such as spent fuel storage, and redirecting safeguards resources toward high priority path steps within the state); 2) **coverage of all plausible acquisition paths**; 3) the use of **state specific features and characteristics**[62]; 3) the continuing evaluation of all relevant information and activities; and 4) the recognition that safeguards processes need to be consistently applied and non-discriminatory.

As already mentioned, in many respects the SLC is intended to continue these existing practices, but also to improve their utilisation, i.e. by *more systematically* applying APA and SSFs – particularly with respect to assessing a State's technical capabilities as well as its nuclear activities -- and putting more emphasis on collaborative analysis, analytical rigor, critical thinking and uniform processes and well-defined procedures.

Importantly, as the IAEA General Conference safeguards resolutions have asserted since 2014, "The SLC is applicable to all States, but strictly within the scope of each individual State's safeguards agreement(s)." As new information about a State's nuclear program arises, it will be reflected in SLAs and used to adjust the focus of safeguards activities accordingly. Such customized SLAs, that align safeguards measures to prioritized, TOs specific to each state, have fundamental implications for how the IAEA plans, conducts, and evaluates safeguards activities, and ultimately how the Agency draws and reports conclusions about a State's compliance with its obligations under its safeguards agreement. Once a methodology for establishing the required level of verification efforts is in place for all SLAs, the Agency will be in a better position to evaluate the effectiveness of safeguards activities based on the attainment of safeguards objectives, rather than based on simply carrying out the planned activities as in traditional safeguards approaches under the Safeguards Criteria and IS.[63]

Thus, based on the historical background and rationale described above, one can credibly argue that the SLC (as described in the 2013 and 2014 SLC reports) provides a framework that is better suited for detecting undeclared activities – or at least better suited for allocating safeguards resources – than a rigid prescriptive, facility-level approach. This framework: (a) looks at the state as a whole, taking all safeguards relevant information into account to improve state evaluations, (b) links safeguards activities directly to the

[62] Now referred to as the State Specific Factors.

[63] In the Secretariat's SLA Improvement Project, which began in 2019 and is stated to be completed in 2022, the IAEA is now fine tuning a new APA/SLA methodology (that includes performance targets) with different SEGs to standardize the methods to ensure that SLAs for states with the same types of safeguards agreements (and similar nuclear fuel cycles) are implemented ***consistently*** to avoid the appearance of bias and discrimination.

achievement of safeguards objectives, (c) integrates headquarters analysis with in-field verification efforts more systematically, and (d) provides the IAEA with the basis and flexibility to concentrate limited resources *more strategically* within a state.[64]

The SLC is intended to create an architecture focused on the attainment of TOs based on a State's safeguards agreement to cover plausible acquisition paths for States with CSAs**,** rather than *mechanistically* carrying out a predetermined list of activities without consideration of the extent to which underlying verification goals had been achieved. In other words, there have been concerns that under traditional safeguards, inspectors focused more on completing the list of activities in the Annual Implementation Plan (AIP) than on the objectives the activities were intended to achieve.

The SLC could help the IAEA prioritize and allocate its safeguards resources more effectively and efficiently, and justify "differentiation without discrimination" in a way that rationally allocates verification effort across the generic safeguards objectives for a specific State. In addition, the SLC could enhance deterrence, by making the timing and nature of inspections and other verification activities less predictable than under the Safeguards Criteria. Furthermore, by targeting priority TOs within a State, the SLA is better suited for directing information collection and analysis at headquarters.

In sum, the goal of the SLC is to use structured analytical processes to make the implementation of more effective international safeguards that is implemented in the most efficient way, and to do so in a politically and technically defensible manner.

3.4 Qualitative Benefits to Help Safeguards Department Work More Effectively

In addition to the advantages described above, the implementation of the SLC could include some aspirational, qualitative benefits that cannot be measured, but have the potential to improve the international safeguards system. The SLC could:

- Contribute to an **institutional culture** where critical thinking is encouraged.
- Promote **collaboration** among and within the SEGs that are responsible for developing SLAs to make greater use of all safeguards relevant information available to the IAEA**.**
- Help country officers and SEG members to more fully **understand the objectives** of their safeguards activities.
- Help the IAEA to **clarify terminology** and to document key assessments.
- Strengthen the basis for **documenting tradeoffs** among safeguards measures with a system for tracking changes in analysis and its implications for the Agency's activities.

4 Implementation of Safeguards Worldwide

This final subchapter shortly discusses the current status of the State-Level Safeguards implementation world-wide. As already mentioned in this chapter, every year the IAEA prepares for its BoGs the SIR. The report, which is "restricted distribution for official use only", presents a full overview of all the safeguards activities carried out by the Agency in the previous year. After discussion at the IAEA BoGs a decision is usually taken to de-restrict and authorize the release of the first part of the SIR document, containing its part A: titled "*Safeguards Statement*" for the year, which presents a compact overview of the findings, and the part B: *"Background to the Safeguards Statement and Summary"* presenting supporting data of the safeguards conclusions. Other sections of the SIR, presenting i.a. safeguards implementation data, remain restricted. On

64 The SLC promotes SLAs and AIPs that are adaptable and responsive to new safeguards relevant information. Through the assessment of SSFs and underlying key assumptions, new information and analysis can lead to reprioritization of TOs, adjustment of performance targets and redistribution of effort.

the basis of the openly available Safeguards Statements and Summaries, it is possible to follow the evolution of the safeguards activities. In this section some of this information is presented to show data related to the State-Level Safeguards and to derive from them a number of general considerations.

4.1 IAEA Safeguards Implementation Statements

In their Safeguards implementation Statements and Summaries[65], the IAEA reports annually on the status of implementation of nuclear safeguards in the States Parties to the NPT and in NPT non-Parties with other safeguards agreements in place. Based on this information, Table 4 provides an overview of the number of States in each combination of safeguards regimes in 2019[66], and Figure 2 highlights the evolution in the period from 2016 (first IAEA Safeguards implementation statement citing the number of SLAs that have been developed) to 2019.

Table 4: Number of NPT and non NPT States[67] in the various Nuclear Safeguards regimes as of 2019 (data source[68]).

Year	2019	Notes
Number of States with Safeguards applied	183[69]	States with a safeguards agreement (CSA + AP; CSA; INFCIRC/66; VOA), i.e. 131 + 44 + 3 + 5 Member States underlined below.
of which, with SLA developed	131	This number is only incidentally the same as that in the line below. There can be, e.g. SLAs for States with no AP, or NWS with a SLA.
Number of States with CSA + AP in place	131[70]	This number has steadily increased over the last years (see Figure 2).
of which, with broader conclusion already drawn	69[71]	This is a subset of the above, for which the IAEA from the ratification of AP, could conduct evaluations and draw the broader conclusion.
of which, with integrated SG	67[72]	This is a subset of the above.
Number of States, party to the NPT, with CSA only (no AP in force).	44	This number decreases over time, as more and more APs are implemented (see Figure 2).
Number of States, party to the NPT, with no CSA in place.	10	No safeguards applied in: Cabo Verde, Equatorial Guinea, Eritrea, Guinea, Guinea-Bissau, Federated States of Micronesia, Sao Tome and Principe, Somalia, State of Palestine, Timor-Leste.
Number of States under INFCIRC/66 Safeguards (non-NPT members)	3	Pakistan, India, Israel.
of which, with AP	1	India.
Number of States with revised SQP into force	62	This number is increasing over time (see Figure 2).
Number of States with original SQP into force	32	This number is decreasing over time (see Figure 2).
Number of NWS with voluntary agreements and AP in place	5	USA, Russia, China, UK, France.

[65] https://www.iaea.org/publications/reports
[66] International Atomic Energy Agency, "Safeguards Statement for 2019," IAEA, Vienna, 2020.
[67] As reported by the IAEA in the Safeguards Implementation Reports, "The designation employed does not imply the expression of any opinion whatsoever concerning the legal status of any country or territory or of its authorities, or concerning the delimitation of its frontiers".
[68] International Atomic Energy Agency, "Safeguards Statement for 2019," IAEA, Vienna, 2020.
[69] And Taiwan, China.
[70] And Taiwan, China
[71] And Taiwan, China
[72] And Taiwan, China

Number of States which are not Parties to the NPT	4	India, Israel, Pakistan (INFCIRC/66) South Sudan. No safeguards applied in: South Sudan
Number of States which announced withdrawal from NPT	1	No safeguards applied in: DPRK

The trends in Figure 2 show a sharp increase of the number of States for which SLAs have been developed between 2017 (64 SLAs developed) and 2018 (126 SLAs developed) with then a little increase in 2019 (131). The graph also highlights the increase of States passing from having only a CSA in place to having a CSA and an AP. With more States adopting the AP, the trends also show an increase of the number of States with a broader conclusion of absence of undeclared material and activities drawn and consequently an increase of the number of States with Integrated Safeguards in force. The number of States having the original text of the Small Quantities Protocol in place constantly decreased in the reference period.

Table 5 reports selected IAEA safeguards facts and figures in 2019, and Figure 3 shows their evolution in the period 2016-2019. The trends show a substantially stable picture, with no game-changing variations.

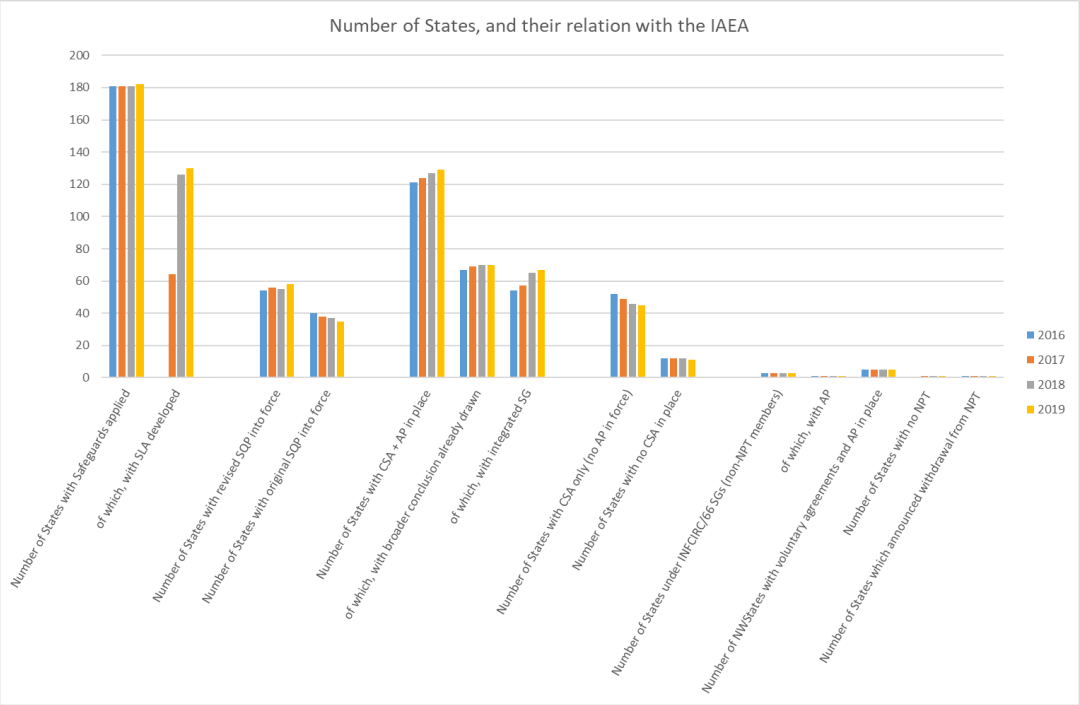

Figure 2: Evolution of the Number of NPT and non-NPT States in the various Nuclear Safeguards regimes in the period 2016-2019 (data sources[73, 74, 75, 76]).

[73] International Atomic Energy Agency, "Safeguards Statement for 2019," IAEA, Vienna, 2020.
[74] International Atomic Energy Agency, "Safeguards Statement for 2018," IAEA, Vienna, 2019.
[75] International Atomic Energy Agency, "Safeguards Statement for 2017," IAEA, Vienna, 2018.
[76] International Atomic Energy Agency, "Safeguards Statement for 2016," IAEA, Vienna, 2017.
[77] International Atomic Energy Agency, "Safeguards Statement for 2019," IAEA, Vienna, 2020.

Table 5: Selected IAEA Safeguards Facts and Figures in 2019 (Data source[77]).

Year	2019
Facilities under Safeguards	717
Material Balance Areas (MBA) containing LOFs under Safeguards	607
SQ of Nuclear Material under Safeguards	216448
t Heavy Water under Safeguards	430.2
Inspections	2179
Design Information Verifications (DIVs)	625
Complementary Accesses	149
Calendar days in the field	13139.5

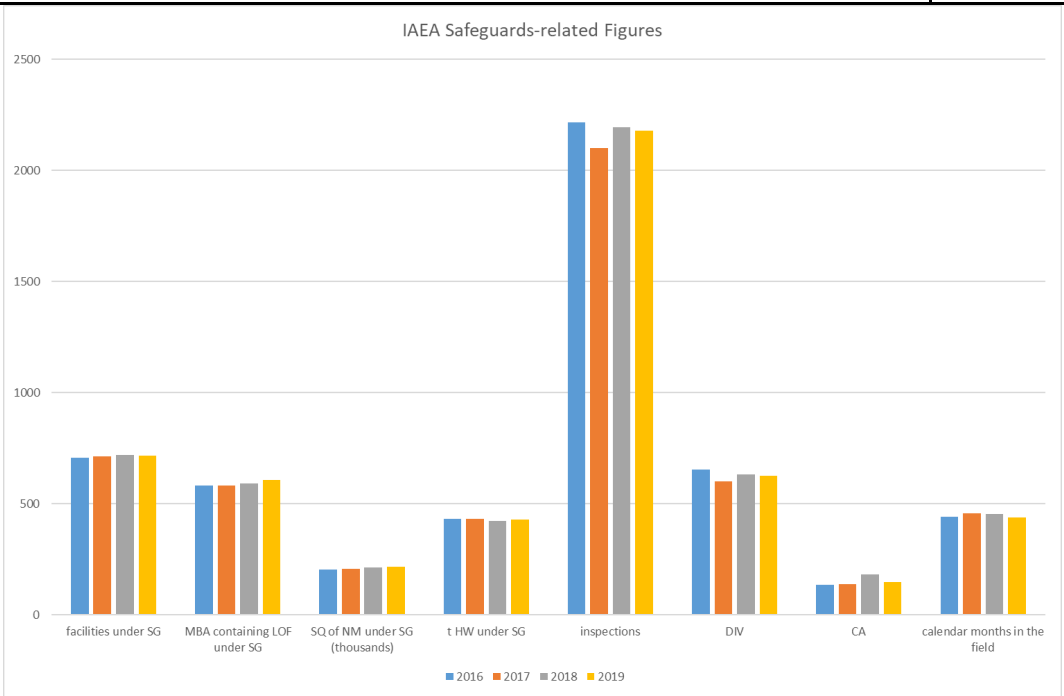

Figure 3: Evolution of Selected IAEA Safeguards Facts and Figures in the period 2016-2019 (Data source 78, 79, 80, 81).

Figure 4 reports the evolution of the IAEA budget in the period 2016-2019, in terms of adjusted regular budget, expenditures and expenditures from extra-budgetary contributions. The adjusted regular budget saw an increase of about 10M€ over four years (about 7.5%). The variability of the expenditures from extra budgetary costs are likely linked to activities related to UN Security Council Resolutions[82].

[78] International Atomic Energy Agency, "Safeguards Statement for 2019," IAEA, Vienna, 2020.
[79] International Atomic Energy Agency, "Safeguards Statement for 2018," IAEA, Vienna, 2019.
[80] International Atomic Energy Agency, "Safeguards Statement for 2017," IAEA, Vienna, 2018.
[81] International Atomic Energy Agency, "Safeguards Statement for 2016," IAEA, Vienna, 2017.
[82] See e.g. International Atomic Energy Agency, "Verification and monitoring in the Islamic Republic of Iran in light of United Nations Security Council resolution 2231 (2015) - Report by the Director General," IAEA , Vienna, 2021.

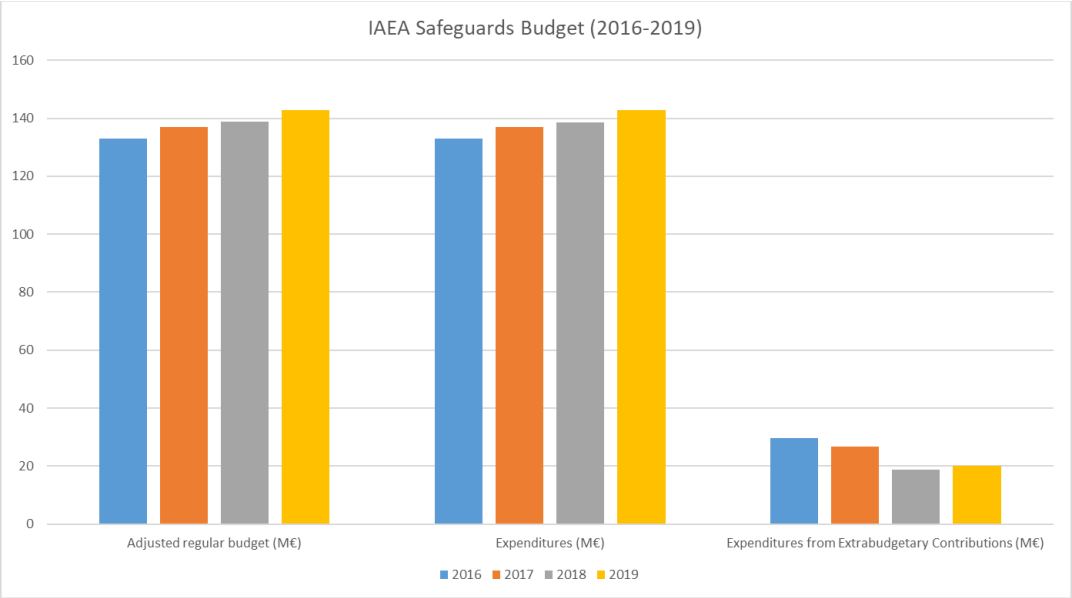

Figure 4: Evolution of IAEA budget in the period 2016-2019.

4.2 Types of Safeguards Conclusions According to the Different Agreements in Force[83]

Currently, NNWS Parties to the NPT can be broadly categorized in four groups:

1. States with a CSA and the AP in force, for which the Agency already drew a broader conclusion;
2. States with a CSA and the AP in force, for which the Agency has not already drawn a broader conclusion;
3. States with a CSA but no AP;
4. States without a CSA.

Figure 5 shows the fraction of Nuclear Material SQs and number of nuclear facilities under the various Safeguards Regimes.

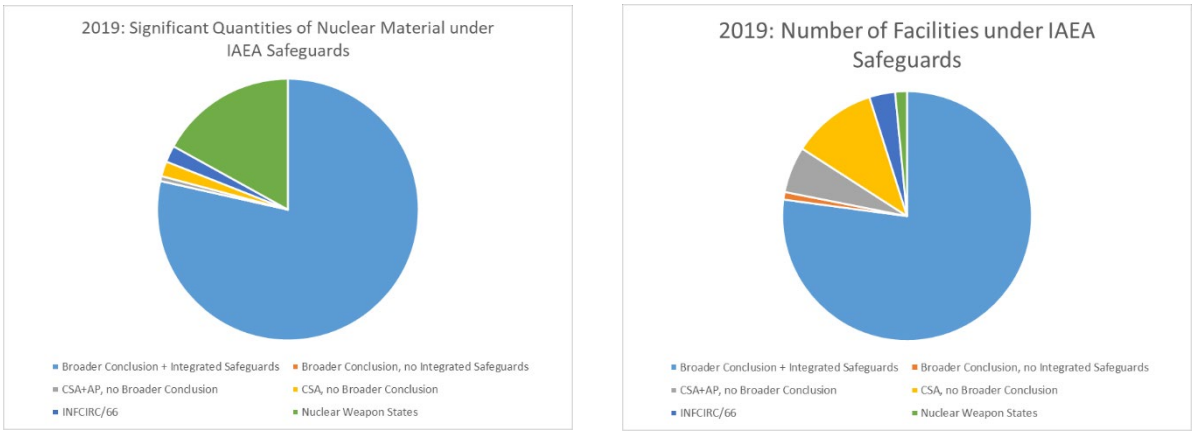

Figure 5: Amount of Nuclear Material SQs and number of nuclear facilities under the various Safeguards Regimes (data source[84]).

For group 1, the Agency can conclude that "*all nuclear material remained in peaceful activities*". For groups 2 and 3 the Agency can conclude that, "*declared nuclear material remained in peaceful activities*". For group 4

[83] The text of this subsection was originally published in "Open Source Analysis in support to the identification of possible undeclared nuclear activities in a State," (F. V. Pabian, G. Renda and G. G. Cojazzi, ESARDA Bulletin, vol. 57, pp. 22-39, 2018); the material here reproduced has been adapted and modified according to the needs of the subchapter.

[84] International Atomic Energy Agency, "Safeguards Statement for 2019," IAEA, Vienna, 2020.

the Agency "*could not draw any safeguards conclusion*". As it can be seen, the IAEA pronounces itself on the status of all the nuclear material in a given State only for group 1, limiting itself to a statement over the *declared* nuclear material for groups 2 and 3.

The pivotal difference between the States in group 1 and those in group 2 is the broader conclusion of absence of undeclared material and activities. As already mentioned, to reach a broader conclusion, the IAEA "*must draw the conclusions of both the non-diversion of the nuclear material placed under safeguards (as described above) and the absence of undeclared nuclear material and activities for the State as a whole*" [85] and the broader conclusion allows the entry into force of the Integrated Safeguards regime and the possibility to take full benefit from State-Level Safeguards approaches[86].

The evaluation and verification of declared nuclear material and activities is conceptually straightforward (even though it might be extremely resource-intensive), and is mainly based on onsite verification activities and measurements. Also, the confirmation of the termination of past nuclear activities and the dismantlement of the related facilities (e.g. a decommissioned civilian NFC programme or part of it) is usually performed through information gathering and Complementary Accesses, foreseen under the AP, and does not represent unsurmountable conceptual challenges as it is known that there was a programme and the conditions of its termination have been stated and could in principle be verified. However, the Agency concludes that there is no undeclared nuclear material or activity in a State when "*the activities performed under an additional protocol have been completed, when relevant questions and inconsistencies have been addressed, and when no indications have been found by the IAEA that, in its judgement, would constitute a safeguards concern*" [87]. The sentence there is "*no indication of undeclared nuclear material or activities*" can be read as "given the verification activities planned and performed on the basis of our past and present knowledge of the State, we found *no indication of undeclared nuclear material or activities*" and therefore it is possible to conclude that "*all nuclear material remained in peaceful activities*". The last *therefore* relies on the inductive inference: "The verification activities performed did not find evidence of an undeclared activity, and they are considered to be sufficient to state that any additional verification activities would not find evidence of undeclared activities". Hence we can conclude that there is no undeclared activity. Since "*[t]he very nature of an inductive argument is to make a conclusion probable, but not certain, given the truth of the premises*" [88], it becomes extremely important to understand how the strength of this conclusion can be characterized and made explicit, i.e. characterize its *dependability*.

While "*Truth with a capital T is an attribute of statements that correspond to facts in all possible contexts*", *dependability* is an attribute of statements that correspond to facts in a "*specified (but often not clearly identified) context*" [89]. A statement is considered to be more or less dependable subject to the degree to which it has been tested. The time and effort that the safeguards inspectorate needs to invest in order to issue a broader conclusion of absence of undeclared material and activities (i.e. let a Member State moving from group 2 to group 1) dependably is conspicuous, and is partially reflected in the amount of Complementary Accesses that the inspectorate performs in the period between the entry into force of the AP and the issue of the broader conclusion and the decrease of Complementary Accesses after its issue.

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[85] International Atomic Energy Agency (IAEA), "IAEA Safeguards Glossary - 2001 Edition," IAEA, Vienna, 2001.

[86] Despite the fact that State-Level Safeguards see their maximum effectiveness and efficiency in a CSA + AP and broader conclusion scenario, the IAEA adopts them also in case of CSA-only safeguards agreements. See GOV/2013/38 and GOV/2014/41 and first and second subchapter.

[87] International Atomic Energy Agency (IAEA), "IAEA Safeguards Glossary - 2001 Edition," IAEA, Vienna, 2001.

[88] H. D. Hales, "Thinking Tools: You can prove a negative," *Think*, vol. 4, pp. 109-112, 2005.

[89] D. I. Blockley, "The Importance of Being Process," *Civil Engineering and Environmental Systems*, vol. 27, no. 3, pp. 189-199, 2010.

In order to illustrate this, Table 6 reports the IAEA efforts in terms of Complementary Accesses in EURATOM Member States. For EURATOM Countries (both NNWS and NWS), the AP entered in force on April 30, 2004 (Other countries joining the EU later had later dates for AP entry into force). From 2005 to 2010 the Agency performed a sustained amount of Complementary Accesses, both on sites and in other locations, with a substantial decrease after 2010.

Table 6: Number of Complementary cceses performed by the IAEA in EURATOM Countries in the period 2005/2013 (data source[90]).

Year	2 hr CAs	24 h CAs	CAs in sites	CAs in other locations	Total nr of CAs in EU
2013	4	5	9	0	9
2012	0	7	5	2	7
2011	0	28	28	0	28
2010	4	40	33	11	44
2009	2	34	32	4	36
2008	2	23	16	9	25
2007	1	27	24	4	28
2006	7	18	23	2	25
2005	19	25	41	3	44

List of Acronyms

AIP Annual Implementation Plan

AP Additional Protocol

APA Acquisition Path Analysis

BoG Board of Governors

CSA Comprehensive Safeguards Agreement

NNWS Non-Nuclear Weapons States

INMM Institute of Nuclear Materials Management

INFCIRC Information Circular

IAEA International Atomic Energy Agency

IS Integrated Safeguards

LOF Location Outside Facility

NFC Nuclear Fuel Cycle

NM Nuclear Material

NPT Treaty on the Nonproliferation of Nuclear Weapons

NWS Nuclear Weapon States

NNWS Non-Nuclear Weapons States

[90] European Commission, "Report on the Implementation of EURATOM Safeguards in 2013," European Commission, Luxembourg, 2014.

SEG State Evaluation Group

SSFs State Specific Factors

SIR Safeguards Implementation Report

SLA State-Level Approach

SLC State-Level Concept

SQP Small Quantities Protocol

SQ Significant Quantity

TO Technical Objectives

VOE Voluntary Offer Agreements

Non-Destructive Assay for Nuclear Safeguards

Paolo Peerani[1], Montse Marin Ferrer[2], Alice Tomanin[3], Steve Tobin[4], Peter Jansson[5], Sophie Grape[5] and Kamel Abbas[6]

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[5] Uppsala university, Sweden
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1 Introduction to Non-Destructive Assay

Both for accountancy and control purposes, presence of nuclear material and properties such as its mass and composition are mainly determined by measurements performed by destructive and non-destructive methods (namely Destructive Assay, or DA, and Non-Destructive Assay, or NDA methods). Common NDA techniques are based on detection and analysis of radiation emitted by an essayed sample. The non-destructive term of NDA techniques refers to the fact that these techniques do often not require preparation of samples to be assayed therefore their physical and chemical states are not altered. Consequently, these samples can be returned into the batched where they were taken from. On the contrary, DA techniques require substantial sample preparations thus assayed samples cannot be returned to their original batches after assay. With respect to NDA, a sample assay with a DA technique is usually time consuming, requires sophisticated and costly instrumentation and equipment for either sample preparations or analysis however provides accurate, precise and sensitive analysis. The main DA techniques are Isotope Dilution Mass, Spectrometry, Secondary Ion Mass Spectrometry, and Inductively Coupled Plasma Mass Spectrometry. While this chapter focused on NDA techniques, all regarding DA techniques are detailed in the DA Chapter of the present book.

There are two types of NDA techniques, passive and active, named so to reflect the fact that the radiation they measure comes either from spontaneous decays, or radiation induced by an external interrogation source on the assayed sample. NDA techniques can also be categorised based on the type of radiation that is measured from an object. The main NDA techniques are classified as gamma-ray assay, neutron assay and calorimetry.

While measurements using NDA techniques may in some cases be time consuming and involve movements or transport of the nuclear material to a dedicated measurement station or instrument, they do not require sample preparations as mentioned or a dedicated laboratory such as DA methods often do. Hence, NDA techniques are often less intrusive, much faster and cheaper than chemical assay and thus reduces the need for sampling. Upon the use of automatic and/or remote handling, they also reduce operator dose exposure. In some cases, such as verification of spent nuclear fuel, NDA is the only viable option.

The development of NDA instruments and analysis techniques reflect a trend towards automation and workforce reduction that is occurring throughout our society. NDA measurements are applied in all fuel-cycle facilities for material accounting, process control, and perimeter monitoring. However, a large fraction of the nuclear material under safeguards is in the form of spent nuclear fuel assemblies, and thus many NDA instruments are designed to assay such object. All uncertainties in this report are specified for a 1-sigma confidence interval unless otherwise noted.

This chapter is structured in several subchapters, based on type of emitted radiation and application. The first subchapter regards calorimetric heat measurements of small samples. The second and third subsections describe respectively gamma–ray spectrometry and neutron-based measurement techniques applied in safeguards. Finally, a fourth subchapter is dedicated to measurements of spent nuclear fuel assemblies because they constitute a large fraction of nuclear material under safeguards. The text describes both available instrumentation for such measurements as well as novel instruments relatively recently developed such as for partial defect verification of spent fuel based using gamma-ray emission tomography.

2 Calorimetric Measurement of Small Samples

Calorimetry is a technique for measuring the thermal power of heat producing samples. It may be used to measure the thermal power of plutonium samples and, in combination with knowledge of the plutonium isotopic mass ratios, calorimetry provides a convenient, accurate and non-destructive measure of the total plutonium mass of the sample [1], [2].

The main advantages of calorimetry are:

- ✓ The assay is independent of sample geometry, nuclear material distribution in the sample, and matrix material composition.
- ✓ Heat standards are directly traceable to National Standards and Plutonium standards are not required.
- ✓ The assay is comparable to chemical assay in precision and accuracy if the isotopic composition is well known.
- ✓ The assay is applicable to a wide range of material forms. Plutonium can be measured in the presence of uranium.

2.1 Objective of the Technique

adioactive decay of any radioactive material produces heat. Calorimetry may be used to measure the thermal power of plutonium samples, and hence to quantify the Pu mass in the sample. The quantitative determination of plutonium by calorimetry is based on the measurement of the heat produced by the radioactive decay of the Pu isotopes, in combination with the knowledge of the plutonium isotopic mass ratios. Calorimetry provides for safeguards activities a convenient, accurate and non-destructive analysis of the total plutonium mass in samples of unknown composition beside the isotopic composition of plutonium, which is determined with gamma-ray or mass spectrometry.

2.2 Scope of Applications

Calorimetry has many advantages with respect to other NDA techniques and it is potentially the most accurate non-destructive method for measuring plutonium mass: calorimetry does not suffer from neutron multiplication effects that hinder other measurement methods and corrections are not required for sample in-homogeneity or chemical form. Unlike destructive analysis, where it is only possible to assay selected samples taken from the item, calorimetry, as other NDA techniques, allows the measurement of the whole item. Due to long time needed for reaching the thermal equilibrium, calorimetry is not yet a routine technique for safeguards in Europe. Nevertheless, in the US calorimetry is used for routine measurements for nuclear materials accountability and shipper-receiver confirmatory measurements for plutonium.

2.3 Principle of Measurement

Plutonium isotopes decay emitting α, β and γ particles, of which the α and β (β^+ and β^-) particles are responsible for the heat generated in the surrounding sample matrix. The calorimetric plutonium assay needs information on the content of americium (^{241}Am) in the measured item, which also contributes to the measured thermal power as an α-emitter and which, as a decay product of ^{241}Pu, is present in practically all plutonium samples. In Table 1 the specific thermal power values of the plutonium isotopes (and of ^{241}Am and ^{3}H) are recorded.

Table 1: Specific thermal power values [1], [2].

Isotope	Main Decay Mode	Specific Power (mW/g)
^{238}Pu	α	567.57
^{239}Pu	α	1.9288
^{240}Pu	α	7.0824
^{241}Pu	β^-	3.412
^{242}Pu	α	0.1159
^{241}Am	α	114.2
^{3}H	β^-	324

2.4 Measurement Technique

The thermal power W (Watts) measured from a plutonium sample in a calorimeter is converted into the plutonium mass (grams) as following:

$$m_{Pu} = \frac{W}{P_{eff}}. \qquad \text{(Eq.1)}$$

The specific thermal power P_{eff} (W/g) of the plutonium sample is calculated from the expression:

$$P_{eff} = \sum_i R_i \cdot P_i \qquad \text{(Eq.2)}$$

where:

Ri = abundance of the i-th isotope (i = ^{238,239,240,241,242}Pu and ^{241}Am) expressed as a weight fraction ($g_{isotope}/g_{Pu}$) and

Pi = a physical constant, the specific thermal power of the i-th isotope in W/g.

One of the most common types of calorimeters in use across the world today for nuclear measurements is the isothermal (servo-controlled) calorimeter. The calorimeter works by maintaining an isothermal enclosure whereby the temperature profile of the calorimeter is kept constant by electrical heaters. Following insertion

of the (Pu) heat bearing source, the reduction in the applied electrical power required to preserve static temperatures is a measure of the decay heat rate.

The measurement chamber of the calorimeter is contained in the thermal element (Figure 1). The thermal element consists of a concentric arrangement of three aluminium alloy cylinders, separated by silicon based thermal semi-conductors. Appropriate nickel resistance thermometer sensors and heater windings, placed inside machined grooves on each of the cylinder surfaces, undertake temperature measurement and control.

The measurement principle involves determining the difference in electrical power supplied to the inner cylinder, to maintain a constant cylinder temperature, after a heat bearing sample is placed into the chamber. As the associated thermal energy is gradually transferred to the inner cylinder by heat conduction and as the inner cylinder must remain at a fixed temperature, the servo controller automatically reduces the applied electrical power. After a period of time, a new thermal equilibrium is achieved (Figure 2). The difference between the old (baseline) and new inner cylinder applied electrical powers being equal to the sample power.

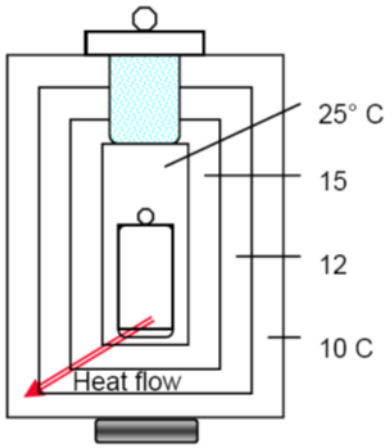

Figure 1: Schematic view of an isothermal air-flow calorimeter.

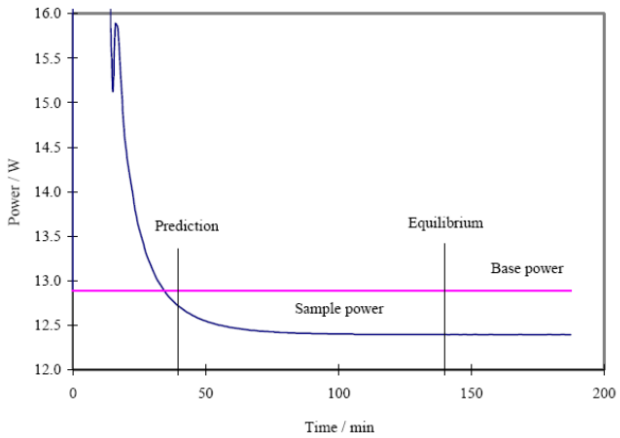

Figure 2: Servo-controlled electrical power applied to calorimeter.

Due to the long time required to reach the thermal equilibrium, the technique is sensitive to the possible change of environmental conditions during the assay. A nearly constant external room temperature is essential for a good performance. This is another reason that makes calorimetry preferably a laboratory technique not suitable for industrial environment. In this frame it is possible to improve the measurement

performance by placing the instrument in a controlled environment, such as a climatic chamber. Figure 3 shows a picture of a plutonium air-flow calorimeter used in PERLA laboratory in EC JRC Ispra.

Figure 3: Plutonium air–flow calorimeter used in JRC Ispra made by ANTECH Inc [4].

2.5 Performance Values

The performance of a calorimetric plutonium assay depends on the thermal power in W as determined by the calorimeter and on the quantity P_{eff} as derived from an external isotope abundance measurement.

Table 2 gives typical performance data [3] for the thermal power measurement obtained with large sample calorimeters and with the new generation of small sample calorimeters using thermopile sensors or combinations of thermopiles and Ni thermocouples (Hybrid calorimeters). The dominant contributions to the random (r) and systematic (s) uncertainties for the small sample calorimeters are due to heat distribution errors and baseline fluctuations.

Table 2: Performance of thermal power measurement [3].

Calorimeter	Thermal power Level (W)	r(%)	s(%)
Large sample calorimeter (Ni thermocouple)	0.1	0.4-0.7	0.1-0.2
	1	0.1-0.3	0.05-0.2
	10	0.05-0.07	0.05-0.2
	100	0.05-0.07	0.05-0.2
Small sample calorimeter (thermopile)	0.001	0.8-1.0	0.2-0.5
	0.01	0.1-0.3	0.1-0.2
	0.1	<0.1	0.1

The above reported performance values refer only to the direct measurement of the thermal power. The total random and systematic uncertainty of a calorimetric plutonium assay is obtained from a combination of the respective uncertainty components for the thermal power and P_{eff} determination. This second component is mainly affected by the uncertainty in the isotopic composition and in particular of the isotopic fractions of ^{238}Pu and ^{241}Am that are the two main contributors. Therefore, it will depend on the technique used for isotopic assay (typically gamma-ray spectrometry).

3 Gamma-Ray Spectrometry

Most radioactive decays are associated with the emission of gamma rays. In general, a radionuclide emits several photons of different energies, which are the signature of that radionuclide for identification in the assayed sample. Accordingly, gamma-ray spectrometry is a qualitative analysis. However, gamma-ray detectors allow not only revealing and discriminating the different gamma-ray peaks of detected radionuclides in an assayed sample but are also able to quantify intensities of those gamma-ray peaks, which allows quantification of activities of those detected radionuclides. Consequently, gamma-ray spectrometry is both qualitative and quantitative analysis method. It is used either for absolute or relative determinations of the activities of the revealed radionuclides in a sample, thus it is used for the determination of nuclear material isotopics such as in the determinations of uranium enrichment or plutonium isotopic composition.

Gamma-ray spectrometry is extremely important for the qualitative information about the isotopic composition. In fact, other quantitative techniques (neutron counting and calorimetry) need the knowledge of the isotopic composition in order to convert the measured quantity (neutron source or thermal power) into a fissile material mass.

3.1 Objective of the Technique

Gamma-ray spectrometry is the most commonly used NDA technique in nuclear safeguards for uranium enrichment and plutonium isotopic composition verifications [5]. Another important field of application are measurements on spent fuel to confirm characteristics, cooling time, initial enrichment or burn-up of fuel assemblies. Gamma-ray spectrometry is also fundamental in the verification of spent nuclear fuel [6], both when the objective with the measurements is to deduce the presence of nuclear material (known as gross defect) and when the objective is to draw conclusions on whether or not a fraction of the fuel material has been diverted (known as partial defect verification).

3.2 Principle of Measurement / Definition of the Physical Principle

A comprehensive explanation on the origin of the gamma-rays, their interaction with matter and their detection by various types of detectors can be found in [7], [8], while this subchapter presents just an overview of selected parts.

The decay of radioactive nuclides is often accompanied by the emission of one or more photons, whose energy is characteristic of the radionuclide itself as mentioned above. Gamma-ray spectrometers are energy-sensitive gamma-ray detectors appropriate for measuring the photon energy. Their output is a so-called gamma-ray spectrum, which shows the number of detected counts as a function of gamma-ray energy. A gamma spectrum can be used to identify the gamma-emitting radionuclides in a material, by correlating the photo-peaks to the characteristic energies of each nuclide. Moreover, the comparison of different peak intensities can be used to derive the absolute or relative abundance of isotopes. Figure 4 shows an example of a gamma-ray spectrum of a plutonium sample acquired with a high purity gamma-ray detector (HPGe) where gamma-ray peaks of three radionuclides (^{241}Am, ^{239}Pu and ^{241}Pu) are indicated.

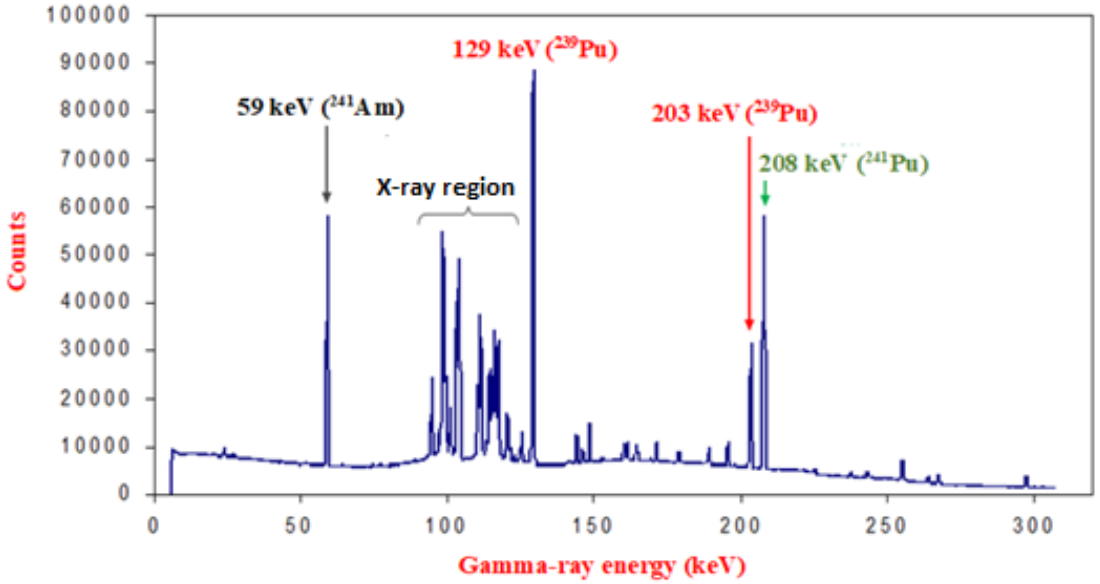

Figure 4: An example of a gamma-ray spectrum of a plutonium sample.

3.3 Measurement Technique/Description of the Implemented Technique

3.3.1 Acquisition of Gamma-Ray Spectra

The gamma-ray spectra are collected using gamma-ray spectrometers which record the gamma-rays and sorts them according to energy. Depending on the specific application, the level of resolution in such gamma-ray spectra vary with the type of detectors chosen. Commonly used detectors are inorganic scintillators such as NaI(Tl) and $LaBr_3$ [9], and semiconductors such as high-purity germanium (HPGe) or cadmium-zinc-telluride (CdZnTe or CZT).

As shown in the illustration of Figure 5, there are three categories of gamma-ray spectrometry for safeguards, which ar based off the used detectors, namely:

- the low energy resolution gamma-ray spectrometry (LRGS), based on NaI scintillators,
- the medium energy resolution gamma-ray-spectrometry (MRGS), based on $LaBr_3$ scintillators or CdTe/CdZnTe semi-conductor detectors,
- the high energy resolution gamma-ray spectrometry (HRGS), which utilises HPGe semi-conductor detectors.

A comparison of efficiencies (ε) and energy resolutions (Res) the four mentioned gamma-ray detectors HPGe, CdZnTe, $LaBr_3$ and NaI is summarised in Table 3.

Table 3: Comparison of efficiencies and energy resolution of HPGe, CdZnTe, LaBr3 and NaI detectors.

Energy Resolution	Efficiency
$\mathbf{Res_{HPGe} > Res_{CdTe/CdZnTe} > Res_{LaBr3} > Res_{NaI}}$	$\varepsilon_{LaBr3} \geq \varepsilon_{NaI} > \varepsilon_{HPGe} > \varepsilon_{CdTe/CdZnTe}$

The technology development of gamma-ray detectors over the last five decades is illustrated in Figure 5 indicating main characteristics of LRGS, MRGS and HRGS based detectors in terms of energy resolution, efficiency and crystal cooling requirements are shown in the diagram of Figure 5.

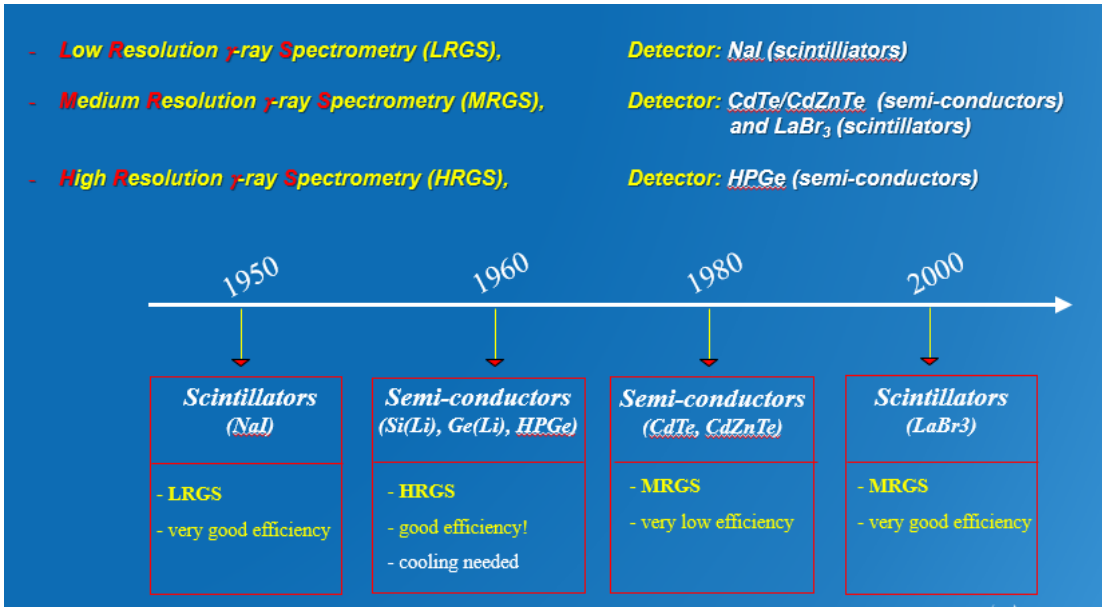

Figure 5: Development evolution of gamma-ray detectors and categories of gamma-ray spectrometry based on energy resolutions of the used detectors (LRGS, MRGS and HRGS).

Detection of gamma-rays relies on the emitted gamma-rays interacting with the detection media through probabilistic processes. The most distinct regions in a gamma-ray spectrum are the full-energy peak and the Compton continuum, which originate from different interactions between the gamma ray and the detector material. In the event of total absorption, all the available energy from the emitted gamma-ray is absorbed in the detector crystal. This results in a single gamma-ray peak in the acquired spectrum (the full energy absorption peak) while Compton interactions result on a continuum in an acquired spectrum. This is because a part of the available photon energy (Compton photons) escapes from the detector crystal. As the Compton Effect has an angular distribution, this results in a detection of a continuum.

Figure 6 shows a gamma spectrum of a source of ^{137}Cs, a radionuclide which emits a single photon energy of 662 keV. The total absorption peak is found at 662 keV, whereas the Compton continuum starts from low energy and ends at 477 keV, i.e. the maximum Compton energy with respect to the emission angle. The Compton peak (184 keV) corresponding to a Compton emission at 180 degrees (backscattering) with respect to the direction of the initial gamma photon is visible in the Compton continuum. This is due to the high probability of the Compton Effect at this angle. X-ray peaks of the detection material, which are induced by the initial gamma-ray (662 keV) or by continuum, are visible. Historically, the intrinsic efficiency of a gamma-ray detector, which is energy dependant, is expressed in percent relative to an efficiency of a cylinder of a 3'' x 3'' NaI crystal in a detection geometry at 25 cm from a point source. The energy resolution is also energy dependent and in practice is energy range of Full Width at Half Maximum (FWHM) of the gamma-ray peak of interest as shown in Figure 6. Beside the efficiency and energy resolution, ratios of gamma peak to valley (see Figure 6) and peak to Compton continuum are also key characteristics for choosing a gamma-ray detector. Nonetheless the different components of the electronic chain and software for pulse processing from the detector crystal all the way to the visualisation and deconvolution of spectra play important role in

terms of accuracy, sensitivity and precision of gamma-ray spectrometry measurements. Figure 7 shows a comparison of typical spectra as generated from HPGe, CdZnTe, LaBr3 and NaI gamma-ray detectors.

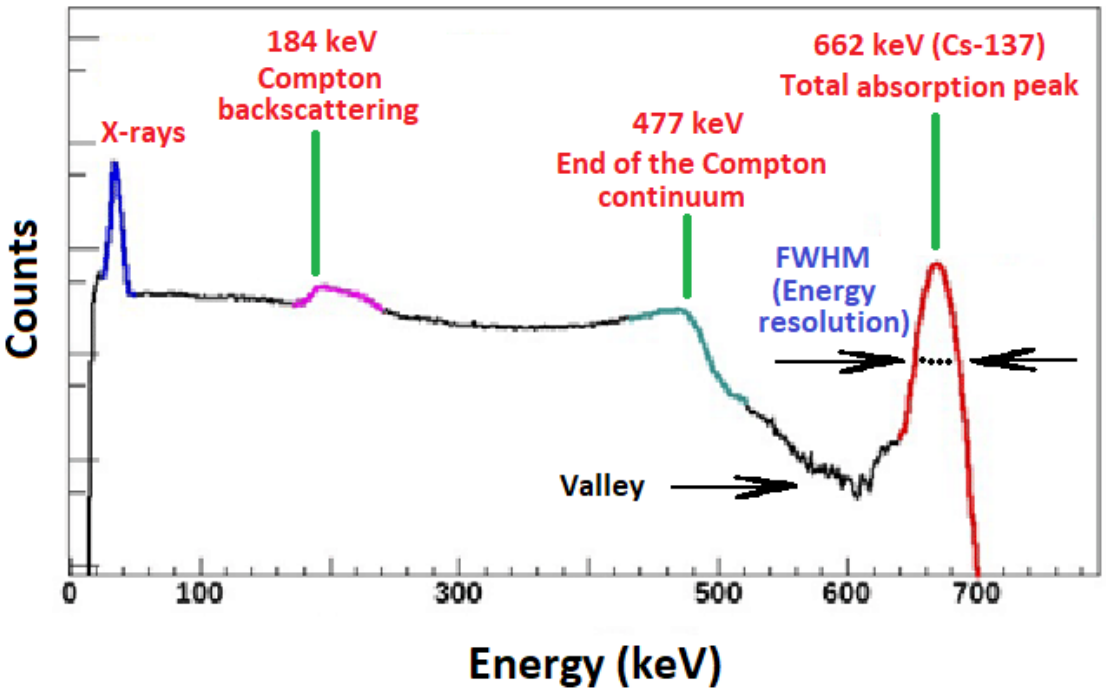

Figure 6: A typical NaI scintillator gamma-ray spectrum of a source of 137Cs radioactive source acquired with a NaI scintillator illustrating the different interaction of gamma photon in a detection material.

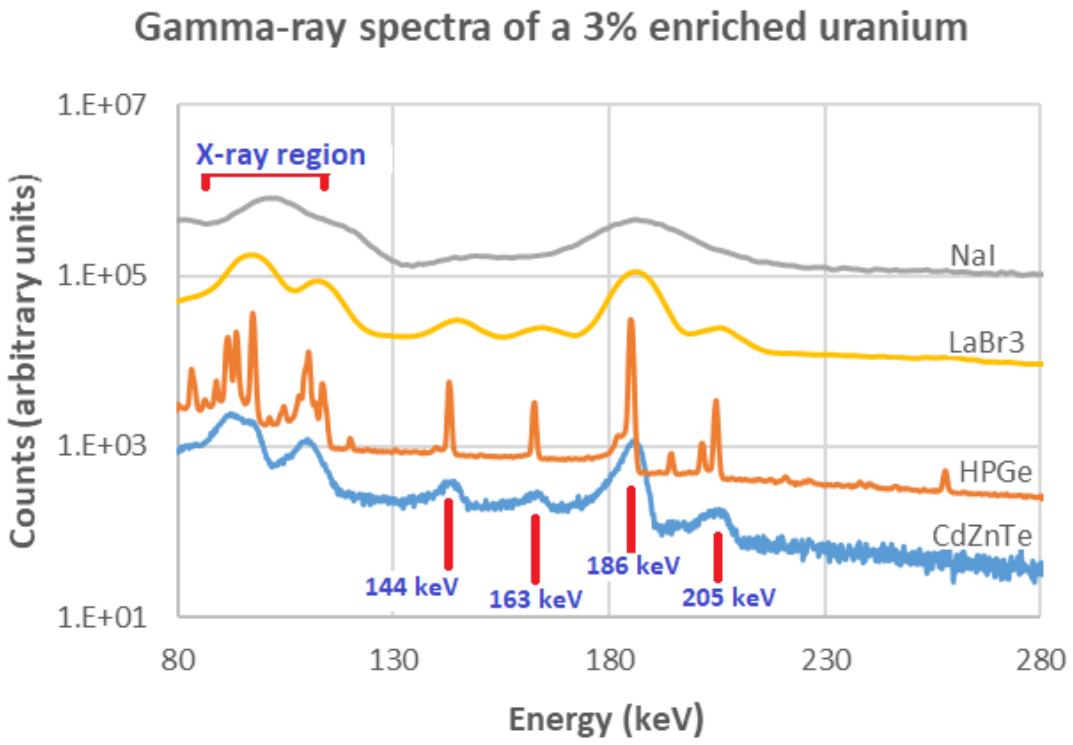

Figure 7: Comparison of uranium spectra from different detector types.

Figure 8 shows a sketch of commonly used electronic instruments for gamma-ray spectrometry based on semi-conductor detector such as HPGe although important evolution was realised in the last 2 to 3 decades. One of the main evolutions regards performance on high counting acquisition through the digitalisation of the chain by substitution of the analogue amplifier by digital signal processing unit (DSP) minimising so acquisition saturation of a gamma-ray spectrometer.

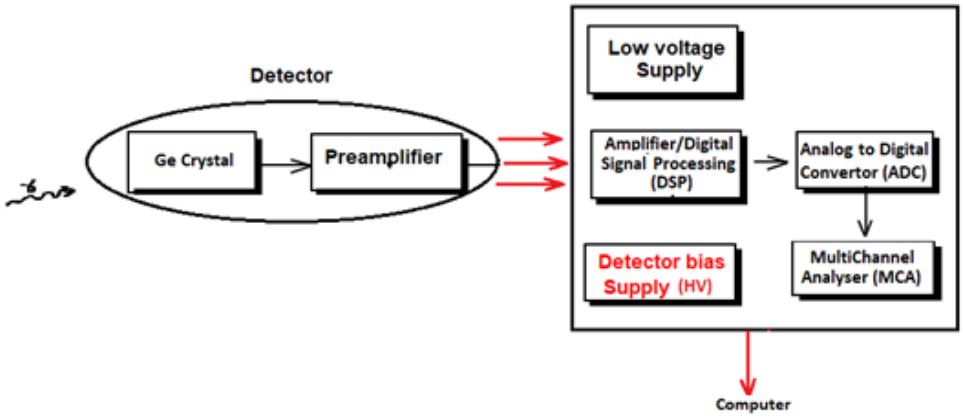

Figure 8: A typical electronic chain for gamma-ray spectrometry. When applicable such as with a liquid nitrogen cooled HPGe detector, the high voltage supply unit (bias supply) includes a circuit to inhibit any voltage output in case the crystal detector is not a proper temperature.

In a scintillator, the interaction of the photon with the crystal results in the excitation of atoms to higher energy states, followed by their immediate relaxation (de-excitation) with consequent emission of the excitation energy in the form of light (scintillations). This light is collected on a photocathode, composed of a material with a high probability of photoelectric effect, resulting in the emission of a number of electrons proportional to the energy of the original photon. These electrons are then increased in number by successive acceleration in an electric field and collisions on metallic dynodes, finally resulting in a charge burst hitting the anode of the photomultiplier tube. A schematic functioning of a scintillator based gamma-ray detector is presented in Figure 9. Scintillators in general and NaI in particular, are characterised by a high detection efficiency, counterbalanced by a poor energy resolution. Due to this last feature they are not suitable for cases involving complex spectra with many closely spaced gamma-ray peaks, such as plutonium. As indicated above, the use of NaI detectors in nuclear safeguards, often referred to as LRGS, is therefore limited to measurements of ^{235}U enrichment in uranium samples. Figure 10 shows a picture of two NaI scintillators.

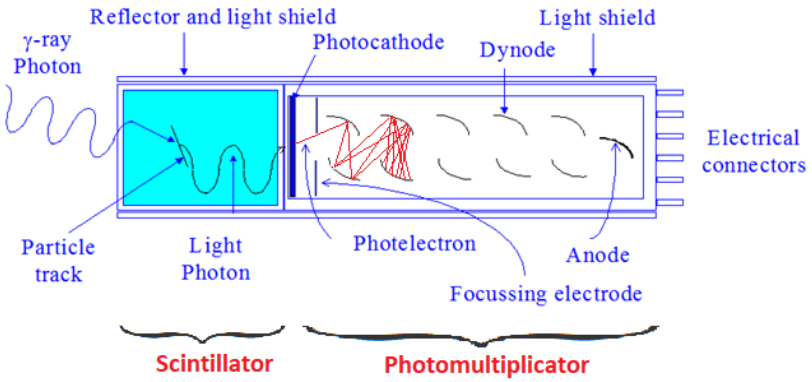

Figure 9: Principle of a scintillator based gamma-ray detector with a photomultiplier tube (PMT).

Figure 10: Example of a NaI scintillator used for safeguards inspector trainings in EC JRC Ispra, Italy.

In semiconductor-based gamma-ray detectors such as HPGe and Cd/ZnTe, the incoming photon "ionises" the crystal and creates electron-hole pairs, which gives rise to a collection of charge at the electrodes thanks to the voltage, which is applied to the semiconductor. As the individual charge carriers are directly related to the output current, detectors of this type tend to be very sensitive to incoming radiation. This collection of charges is illustrated in Figure 11.

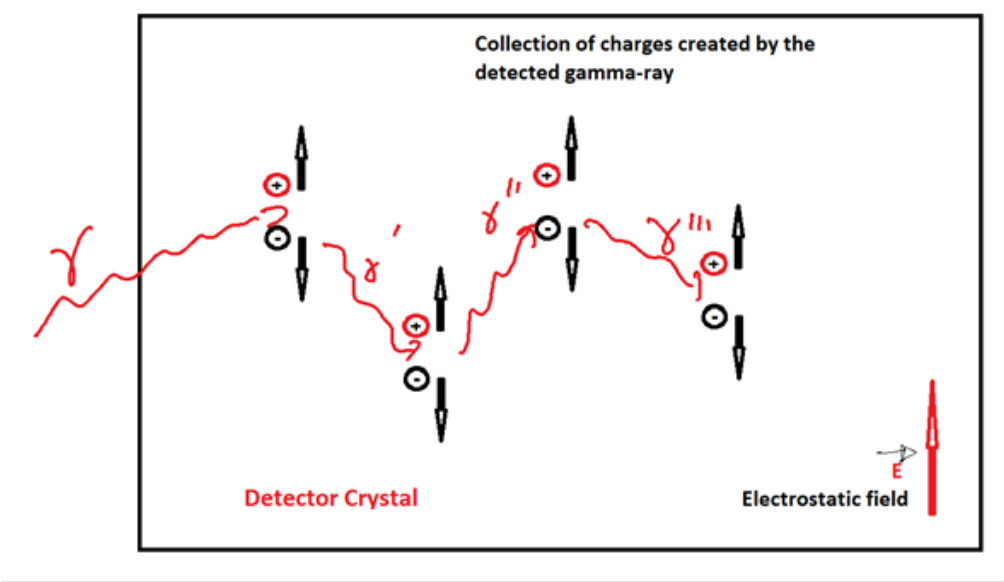

Figure 11: Illustration of ionisation of the detection media and collection of charges in a semi-conductor based gamma-ray detector.

This provides a very good (i.e high) energy resolution, which often comes at the expensive of a high sensitivity to thermal noise. HPGe detectors are for instance able to provide good energy resolution but unfortunately, germanium crystals cannot be operated at room temperature. In order to guarantee an optimum semiconductor performance, the germanium crystal has to be maintained at very low temperatures, i.e., typically using liquid nitrogen (77 K) or electro-mechanical systems. Due to the required cooling, germanium detector units tend to be relatively heavy and large (see Figure 12, [10] and [11]). The so-called HRGS is the preferred technique for plutonium isotopic composition determination as it is able to resolve complex gamma-ray spectra of plutonium due to numbers of plutonium isotopes and gamma-ray peaks to be considered where it is important to be able to separate full-energy peaks in a spectrum, HRGS is also applied to measure uranium enrichment. For applications where portability or accessibility is an

Figure 12: Pictures of commonly used HPGe detectors [12] and [13].

important requirement, other types of crystals have been introduced, such as Cadmium-Zinc-Telluride (CdZnTe or CZT), which provides reasonable energy resolution at room temperature. CdZnTe or CZT detectors have a poorer energy resolution than Ge-detectors. They are used to measure uranium enrichment and to perform attribute verification of spent fuel (detection of fission products).

A well-known gamma-ray detector by the safeguards inspectors for uranium enrichment verifications is the hand held NaI scintillator, which is called HM5 or Identifinder (Figure 13). It is also used in nuclear security such as in border control.

Figure 13: A picture of an HM5 (or Identifinder) used for uranium enrichment verifications. It also measures dose rates. Picture taken in PERLA laboratory, a research and training laboratory of EC JRC Ispra site (Italy).

Figure 14 shows a picture of the latest advance in the portable germanium detector area, which is the Cryo3, developed by an LLNL/LBNL collaboration. This light-weight (4.5 kg) cooler uses off-the-shelf mechanical coolers to cool the ORTEC-supplied crystal. The cooler uses 15 Watts to cool the detector. In addition to the normal vacuum jacket, the detector includes a high-pressure nitrogen jacket as thermal insulation. It operates up to 6 hours on two camcorder batteries.

Gamma-ray spectrometry is an important NDA technique in nuclear safeguards and required sophisticated instrumentation that requires deep hand-on trainings. Figure 15 presents a view of a lab setting for safeguards inspector training on uranium enrichment and plutonium composition verifications.

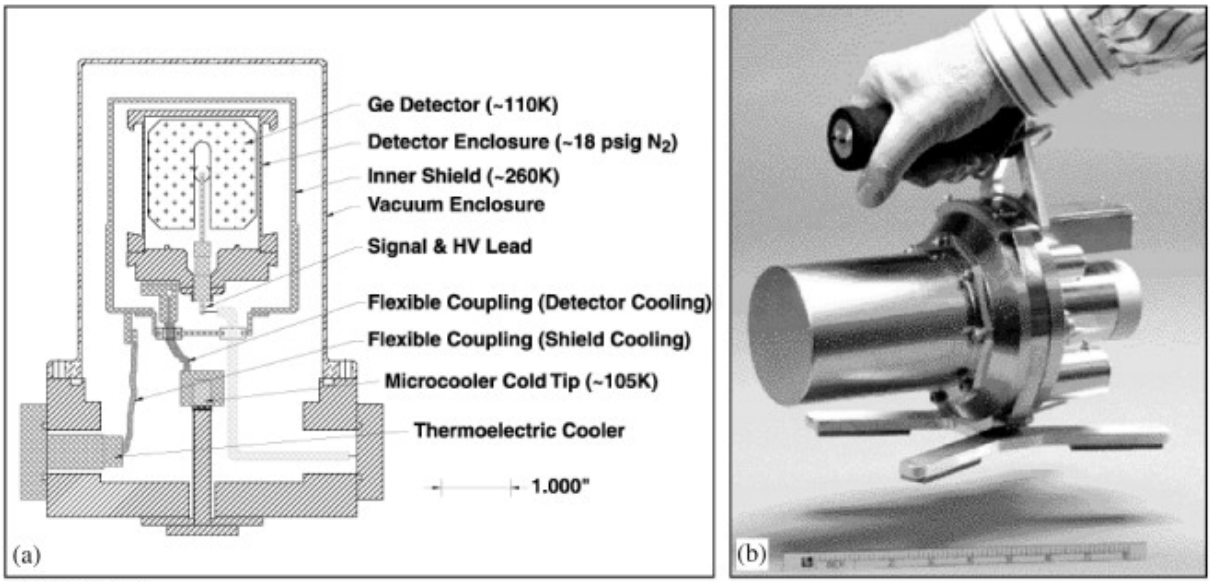

Figure 14: A picture of Cryo3 and some of it characteristics, which is the latest advance hand-held germanium detector [14].

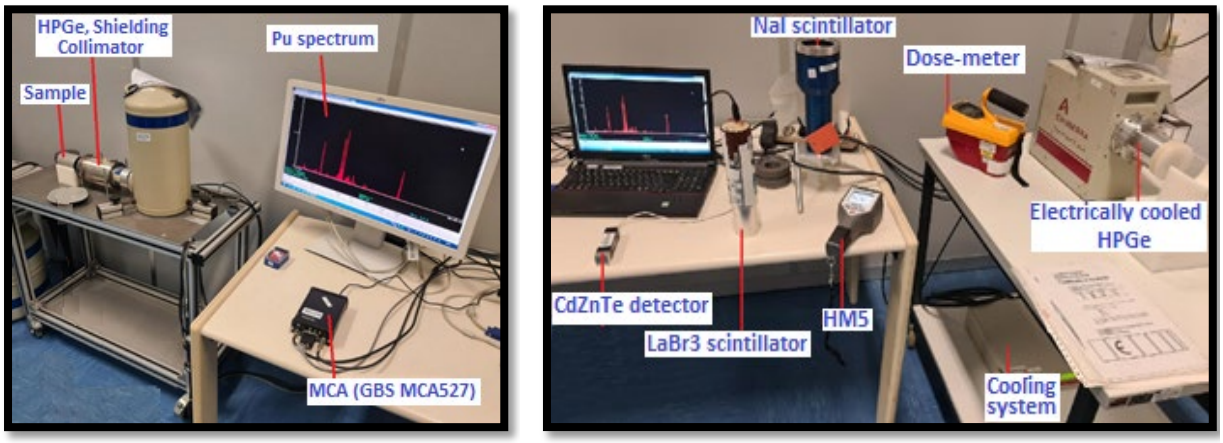

Figure 15: Views of a lab setting for safeguards inspectors on uranium enrichment and plutonium composition verifications. GBS MCA527 is a compact gamma-ray spectrometry electronic chain [15].

For both scintillators and semiconductors, the interaction of a photon with the detector results in an electric signal, whose amplitude is proportional to the energy of the incoming photon.

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

3.3.2 Analysis of Gamma-Ray Spectra from Small Samples

Once a spectrum has been acquired, it has to be evaluated, in order to deduce information about the object under assay and to e.g. derive the isotopic composition. Depending on what one wants to know about the sample or object, the spectrum can be analysed in different ways.

For detecting the presence of different radionuclides, there is a large number of commercially available softwares that can be used to analyse the spectrum. Beside acquisition of gamma-ray spectra, these softwares are able for instance to perform peak fitting, background subtraction, peak intensity calculation, external or intrinsic calibration, calculation of the relative isotopic abundance, identify peaks as belonging to different isotopes and perform accurate quantitative analysis.

As mentioned before, they provide information on the availability and properties of different peaks in the spectrum. This information can be used to identify the presence of isotopes in the sample, and to, for instance, verify nuclear fuel properties (as is further discussed in the subchapter on spent fuel verification).

With respect to the analysis of small samples and specifically for determining uranium enrichment, there are basically two methods available for the analysis of spectra:

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

The **infinite thickness method** is applied only for uranium enrichment measurements, and is based on a calibration using reference samples. According to this approach, the most prominent gamma emission of 185.7 keV from the decay of ^{235}U is measured under a well-defined geometry (i.e., solid angle of the sensitive detector volume relative to the gamma source). The measured counting rate of the 185.7 keV photons is proportional to the ^{235}U abundance. The required infinite sample thickness ranges from about 0.25 cm for metal samples to about 7 cm for UF_6 with a density of 1 g/cm3. The method is best suited for bulk samples (e.g., uranium oxides and fluorides in storage containers), which easily meet the infinite thickness requirement. Enrichment measurements based on the enrichment meter principle require physical standards containing a sufficiently large amount of Uranium reference material for calibration.

Uranium enrichment measurements based on **the intrinsic calibration method** avoid the need for calibration with physical standards. Here, the isotopic ratios of ^{235}U and ^{238}U are determined from the measured gamma-ray spectrum using corresponding gamma and X-rays from proper gamma-peaks or of those of their decay products (such as the peak of 1001 keV ^{234}Pa, which is a daughter of ^{238}U), taking into account physical phenomena such as the energy dependence of detector efficiency, self-absorption in the sample and attenuation in the container and filters.

In nuclear safeguards, any plutonium isotope is of safeguards concern except if the ^{238}Pu contribution is greater than 80%. The different plutonium isotopes, however, have different properties and there are reasons to learn as much as possible about the sample, such as to determine the plutonium composition in a sample. With respect to the analysis of gamma-ray spectra from plutonium samples, a major advancement was achieved with calculation codes for isotopic verifications. These codes are applied for both uranium enrichment and isotopic composition of plutonium verifications. The Multi-Group Analysis (MGA) code is the first commonly used in nuclear safeguards, it exploits the complex low-energy XKα region (94-104 keV) of a plutonium gamma-ray spectrum for the isotope analysis [16]. Since this spectral region contains the most abundant plutonium gamma and X-rays detectable in a gamma-ray spectrum from plutonium in the presence of Am, the use of MGA code enables relatively precise isotope abundance determinations from gamma-ray spectra accumulated in relatively short counting times (5-15 min) depending on the assayed sample.

For uranium spectra, the method again uses analysis of the XKα region (89-99 keV), where fairly abundant but strongly overlapping gamma and X-ray signatures from the ^{235}U and ^{238}U daughter nuclides ^{231}Th and ^{234}Th occur. This approach requires secular equilibrium between ^{238}U and its daughter nuclides, which is reached about 80 days after chemical separation: the method is, therefore, not suited for freshly separated uranium materials. The Multi Group Analysis calculation code dedicated for uranium enrichment is called MGAU. This is the preferred uranium enrichment verification method when uranium standards or accurate efficiency curve of the used gamma detector (in the range X-rays to at least 1.001 MeV as mentioned above) are not available.

Beside MGA/MGAU codes, FRAM ([17], [18], [19] and [20]), which stands for Fixed-energy Response-function Analysis with Multiple efficiencies, is an important recently (about two decades) developed and validated code for isotopic composition of nuclear material namely uranium and plutonium with comparable reliability with respect to MGA/MGAU. FRAM performs self-calibration using several gamma-ray peaks and offers more flexibilities for setting up analysis parameters. FRAM analyses gamma-ray spectra of HPGe, CdTe, CdZnTe, and $LaBr_3$ detectors in the energy range from 30 keV up to more than 1 MeV. Nowadays, there is a need for such codes although there are several under development or validation. The results of those developments are periodically reported in international meetings such as the last workshop organised by IAEA in 2021 as shown in Figure 16.

Table 4 presents the commonly used calculation codes for gamma-ray spectrometry analysis in safeguards for either for uranium enrichment, plutonium isotopic composition verifications and attribute tests, which prove that the assayed sample is a nuclear material or generated from a nuclear fuel cycle by identifying for instance nuclear material or key fission products. The accuracy of these codes for uranium enrichment and plutonium isotopic composition verification relies on the homogeneity and for most of cases on the condition of the infinite thickness condition of assayed samples beside the representativeness of the reference samples used for calibration.

Figure 16: Example of an announcement layout of a workshop on nuclear material isotopic verification organised by IAEA in 2021. The complex X-ray region is well illustrated.

A drawback of the gamma-ray spectrometry technique is the lack of measurement capability for the isotope ^{242}Pu as it is very low specific gamma activity. ^{242}Pu does not manifest itself with a detectable gamma-ray signature in a plutonium gamma-ray spectrum. Therefore, recourse has to be made available to isotope

correlation techniques for an estimate of the abundance of this isotope. The uncertainty in the estimated ^{242}Pu abundance reduces the overall accuracy of a complete gamma-ray spectrometric plutonium isotopic analysis made on materials containing a notable fraction of this isotope. Gamma-ray spectrometry is also used in for attribute tests to prove that the assayed sample is a nuclear material or generated from a nuclear fuel cycle by identifying for instance nuclear material or key fission products.

Table 4: Commonly used calculation codes for gamma-ray spectrometry analysis used in safeguards for either for uranium enrichment, plutonium isotopic composition verifications and attribute tests, which prove that the assayed sample is a nuclear material or generated from a nuclear fuel cycle by identifying for instance nuclear material or key fission products. Attribute test uses gamma-ray signatures to establish a presence of nuclear material.

Codes	Application	Detector type	Remarks
^{235}U	U enrichment	NaI	Calibration requires 2 standards. Wall thickness correction not allowed
NaIGEM			Calibration with 1 standard Wall thickness correction allowed
SPEC, MCA	Attribute test		
UF6	U enrichment	Planar HPGe	Calibration with at least 1 standard
MGAU			No calibration required
FRAM			No calibration required
MGA	Pu isotopic composition		No calibration required
FRAM			No calibration required
SPEC, MCA	Attribute test	HPGe – Coaxial	
UF6	U enrichment	CdZnTe	Calibration with at least 1 standard
^{235}U			Calibration requires 2 standards. Wall thickness correction not allowed
MGAU			No calibration required
FRAM			No calibration required (under validation by safeguards authorities)
FP	Attribute test on spent fuel		

3.3.4 Performance Values for Gamma-Ray Spectrometry

For uranium enrichment measurement there is a variety of methodological possibilities based on the choice of the detector CdZnTe (CZT) and of analysis method. Table 5 compares typical performance values for some combinations [21] as a function of the enrichment range. In this table CT stands for counting time in seconds, and *r* and *s* stand for the contributions to the total measurement uncertainty derived from the statistical (random) and systematic components respectively.

Table 5: Performance values for gamma-spectrometric enrichment measurements on low-enriched uranium oxide materials (CT = counting time in s) [21].

U Enr. (%)	Infinite thickness method									Intrinsic calibration method					
	HRGS (Ge)			LRGS (NaI)			MRGS (CZT)			HRGS (Ge)			MRGS (CZT)		
	CT	r(%)	s(%)	CT	r(%)	s(%)	CT	r(%)	s(%)	CT	r(%)	s(%)	CT	r(%)	s(%)
0.3-0.7	360	2	1	360	3	1	1200	10	1	360	8	5			
										3600	3	5			
2-4	360	0.7	0.5	360	1	0.5	1200	3	1	360	2	1	10^4	10	5
										3600	1	1			
5-10	360	0.5	0.5	360	0.5	0.5	1200	3	1	360	2	1	10^4	10	5
										3600	1	1			

For plutonium isotopic composition the choice of HPGe in combination with intrinsic calibration is the only NDA option practically applied on site under inspection as it is less burdensome and less time consuming as no standards nor calibration is required. Table 6 shows typical performance values for HRGS technique for different plutonium compositions. The random component of the uncertainty is based on the assumption of a typical counting time of 10 to 20 minutes. The systematic uncertainty is estimated based on the use of a well-known isotopic ratio of ^{242}Pu as it doesn't have any gamma-peak for gamma-ray spectrometry analysis while other plutonium do have (main peaks: ^{238}Pu, 153 keV; ^{239}Pu: 129 keV; ^{240}Pu: 104 keV, ^{241}Pu: 125 keV; ^{242}Pu: no peak). If the ^{242}Pu abundance is not known meaning, it has to be computed from isotopic correlations, the systematic uncertainty can increase significantly, being dominated by the uncertainty of the ^{242}Pu content.

Table 6: Performance values for Pu isotope assay in PuO_2 and MOX [21].

Type of plutonium	Isotope	r(%)	s(%)
Low burnup ~< 20 GWd/t)	^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu ^{241}Am	3 0.2 1 1 1	5 0.1-0.2 0.3-1 0.2-0.6 0.5
High burnup ~> 40 GWd/t	^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu ^{241}Am	1 0.5 1 1 1	1 0.2-0.4 0.5-1 0.5-1 1

4 Neutron Assay

Contrary to γ-radiation, which is a major component of the natural radiation background and is characteristic of the decay process of several common radioisotopes, neutron radiation is characteristic of only a few

nuclear reactions, most of which involve special nuclear material (SNM). For this reason, the detection of neutrons has found special applications in the fields of nuclear safeguards and security, where it is used as a signature of the presence of fissile and special nuclear materials such as uranium and plutonium isotopes.

For the interest of safeguards application, neutrons can be produced by spontaneous fission, by neutron-induced fission, and by reactions with alpha particles or photons. In many cases these processes yield neutrons with unusually low or high emission rates, distinctive time distributions, or markedly different energy spectra.

4.1 Spontaneous and Induced Nuclear Fission

The spontaneous fission of uranium, plutonium or other heavy elements is an important source of neutrons. Unstable elements with a mass number greater than the ones in the stability region tend to undergo **fission** (the splitting of nuclei) to reach the stable region. During the fission process, two or three neutrons are emitted at the same time, the multiplicity depending on the isotope. Experimentally, we find that spontaneous fission reactions occur for only the very heaviest nuclides those with mass numbers equal or higher than 230.

We don't have to wait, however, for rare spontaneous fission reactions to occur. By irradiating samples of heavy nuclides with slow-moving thermal neutrons, it is possible to **induce** fission reactions. When ^{235}U absorbs a thermal neutron, for example, it splits into two particles of uneven mass and releases an average of 2.5 neutrons, as shown in the figure below (Figure 17).

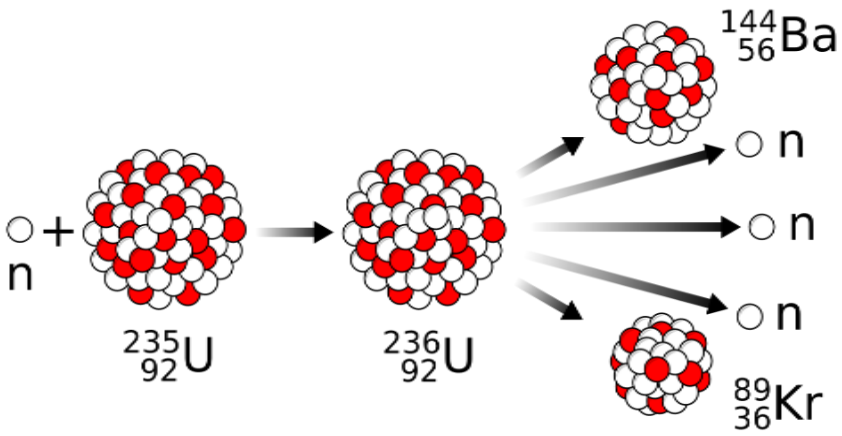

Figure 17: Schematic of an induced fission process (source A MikeRun, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons).

Among the even-even isotopes with high spontaneous fission yields there are ^{238}U, ^{238}Pu, ^{240}Pu, ^{242}Pu, ^{242}Cm, ^{244}Cm and ^{252}Cf. However, isotopes with odd neutron numbers can easily be induced to fission if bombarded with low-energy neutrons: these nuclei are called **fissile.**

4.2 Neutrons from (α,n) Reactions

Nuclei can decay spontaneously by alpha- or beta-ray emission as well as by fission. Alpha particles can also produce neutrons through (α,n) reactions with certain elements. This source of neutrons can be comparable in

intensity to spontaneous fission if isotopes with high alpha decay rates such as ^{233}U, ^{234}U, ^{238}Pu or ^{241}Am are present.

Reactions with energetic alpha particles are possible in low-Z elements. Then, (α,n) reactions can occur in compounds of uranium and plutonium such as oxides or fluorides and in elements such as magnesium or beryllium that may be present as impurities. An important characteristic of neutrons from (α,n) reactions is that only one neutron is emitted in each reaction. These events constitute a neutron source that is random in time with a multiplicity of 1. Both neutron coincidence and multiplicity counters exploit this characteristic to distinguish between spontaneous fission neutrons and neutrons from (α,n) reactions.

4.3 Isotopic Neutron Sources

As with any other radioisotopes, neutron sources have nowadays many useful applications in training, education, research and industry. In nuclear safeguards, they are used for inspections, development and calibration of instruments as well as training and modelling validations. There are several neutron sources of common use in safeguards such as ^{252}Cf, which is the most commonly used as a spontaneous fission neutron source; it can be fabricated in very small sizes and still provide a strong source for a practical period of time. For some applications it is important to remember that ^{252}Cf neutrons are emitted with an average multiplicity of 3.757. Thus they are strongly correlated in time and will generate coincidence events.

Sources that emit random, uncorrelated neutrons can be manufactured by mixing alpha emitters such as ^{238}Pu or ^{241}Am with beryllium, lithium, fluorine, or other elements in which (α,n) reactions are possible. Two common (α,n) sources in use today are $^{241}AmBe$ and $^{241}AmLi$:

- ✓ The **^{241}AmBe** sources are compacted and relatively inexpensive and do not require much gamma ray shielding. However, the high energy spectrum permits (n,2n) reactions that will produce coincidence counts.
- ✓ The **^{241}AmLi** sources are less compact and more expensive and require tungsten shields against the intense 59 keV gamma rays from americium decay. Because of their low-energy neutron spectra, they are the most widely used sources for sub threshold interrogation in active assay and for random-neutron check sources in passive coincidence counting.

Additionally, it is worth mentioning that neutrons can be produced by T(d,n)α fusion reaction in a portable DT generator. Although such neutrons have a much higher energy than those generated by $^{241}AmLi$ sources, D-T generators are currently being considered for active interrogation in few safeguards application, as $^{241}AmLi$ sources are not produced anymore and the old ones are very difficult to replace. Equally neutrons can also be produced by D(d,n)^{3}He in portable D-D generator without the regulatory of tritium of D-T generator.

4.4 Neutron Interaction with Matter

Like gamma rays, neutrons carry no charge and therefore cannot interact with matter by means of the Coulomb force, which dominates the energy loss mechanisms for charged particles and electrons [7]. Neutrons can also travel through many centimetres of matter without any type of interaction and thus can be totally invisible to a detector of common size. When a neutron does undergo interaction, it is with a nucleus of the absorbing material. As a result of the interaction, the neutron may either totally disappear and be replaced by one or more secondary radiations, or may undergo a significant change of its energy or direction.

In contrast to gamma rays, the secondary radiations resulting from neutron interactions are almost always heavy charged particles. These particles may be produced either as a result of neutron-induced nuclear reactions, or they may be the nuclei of the absorbing material itself, which have gained energy as a result of

neutron collisions. Most neutron detectors use some type of conversion of the incident neutron into secondary charged particles, which can be detected directly.

The relative probabilities of the various types of neutron interaction change dramatically with neutron energy. In somewhat of an oversimplification, we will divide neutrons into two categories on the basis of their energy, either "fast neutrons" or "slow neutrons", and discuss their interaction properties separately. The dividing line will be at about **0.5 eV**, or about the energy of the abrupt drop in absorption cross section in cadmium (the cadmium cut-off energy).

4.4.1 Slow Neutron Interaction

For slow neutrons, significant interactions include **elastic scattering** with absorber nuclei and a large set of neutron-induced nuclear reactions. Because of the small kinetic energy of slow neutrons, very little energy can be transferred to the nucleus in elastic scattering. Consequently, this is not an interaction on which detectors of slow neutrons can be based on. The slow neutron interactions of real importance are neutron-induced reactions that can create secondary radiations of sufficient energy to be detected directly. Because the incoming neutron energy is so low, all such reactions must have a positive Q-value to be energetically possible. In most materials, the radiative capture reaction ((n,γ) reaction) is the most probable and plays an important role in the neutrons' attenuation shielding. Radiative capture reactions can be useful in indirect detections of neutrons using activation foils. However, they are not widely applied in active neutron detectors because the secondary radiation takes the form of gamma rays, also difficult to be detected. Reactions such as (n,α), (n,p) and (n, **fission) are much more attractive** because the secondary radiations are charged particles.

4.4.2 Fast Neutron Interactions

The probability of most neutron-induced reactions potentially useful in detectors drops off rapidly with increasing neutron energy. The importance of scattering becomes greater, however, because the neutron can transfer an appreciable amount of energy in one collision. The secondary radiations in this case are **recoil nuclei**, which have gained a detectable amount of energy from neutron collisions.

4.5 Neutron Detectors

There are different types of neutron detectors available, and their principles differ depending on their principle of operation as well as what they are designed to detect. In the following sections we will focus on the two families of neutron detectors that are used in safeguards applications: the gas-filled detectors (with particular focus on ^{3}He proportional counters, which have been for long the golden standard in neutron coincidence counting) and the scintillation detectors (which have recently received attention as potential replacement of ^{3}He following the reduced availability and price increase of this gas).

4.5.1 Gas-Filled Detectors

Gas-filled detectors were among the first devices used for radiation detection. They may be used to detect either thermal neutrons via nuclear reactions or fast neutrons via recoil interactions. The exterior appearance of a gas detector is that of a metal cylinder with an electrical connector at one end (occasionally at both ends for position-sensitive measurements). The detection of neutrons requires the transfer of some or all of the neutrons' energy to charged particles. The charged particle will then ionise and excite the atoms along its path until its energy is exhausted.

4.5.1.1 Proportional Counters

When the electric field strength is large enough, the primary electrons can gain sufficient energy to ionise the gas molecules and create secondary ionisation. If the field strength is increased further, the secondary electrons can also ionise gas molecules. This process continues rapidly as the field strength increases, thus producing a large multiplication of the number of ions formed during the primary event. This accumulative amplification process is known as avalanche ionisation.

Gas-filled detectors typically employ ^{3}He, ^{4}He, BF_3 or CH_4 as the primary constituent, at pressures of less than 1 to about 20 atm depending on the application.

4.5.1.2 The ^{3}He Proportional Counter

The gas ^{3}He is widely used as a detection medium for neutrons through the reaction $^{3}He(n, p)\ ^{3}H$ with Q_{value}= 0.764 MeV. For reactions induced by slow neutrons, the Q_{value} of 0.764 MeV leads to oppositely directed reaction products with energies E_p = 0.573 MeV and $E_{H\text{-}3}$ = 0.191 MeV.

The thermal-neutron cross section for this reaction is 5330 barns and its value falls off with a 1/v energy dependence. The reaction cross section is strongly dependent on the incident neutron energy E. Because of this strong energy dependence, it is customary to embed ^{3}He detectors in approximately 10 cm of polyethylene or other moderating materials to maximise their counting efficiency. Although ^{3}He is commercially available, its relatively high cost is a factor in some applications.

The process of detecting thermal neutrons involves first moderation then capture in a ^{3}He proportional counter embedded in the moderator. A neutron from spontaneous fission has an initial energy of about 2 MeV, and will be moderated to room temperature (corresponding to 0.025 eV), by about 27 collisions in hydrogen. The capture reaction is:

$$N + {}^{3}He \rightarrow p + {}^{3}H + 765keV \qquad \text{(Eq. 10)}$$

The reaction energy of 765 keV appears as the kinetic energy of the proton and triton, and is collected as a charge pulse because of the high voltage applied across the tube wall and its central anode wire.

Typically, integrated circuits are used to amplify the tube output pulses, set the counting threshold, and convert the pulses above the threshold to digital pulses. These modules are composed by preamplifier + amplifier + discriminator and they will be called amplifiers. Figure 18 shows the structure and a pulse height spectrum of a typical ^{3}He proportional counter.

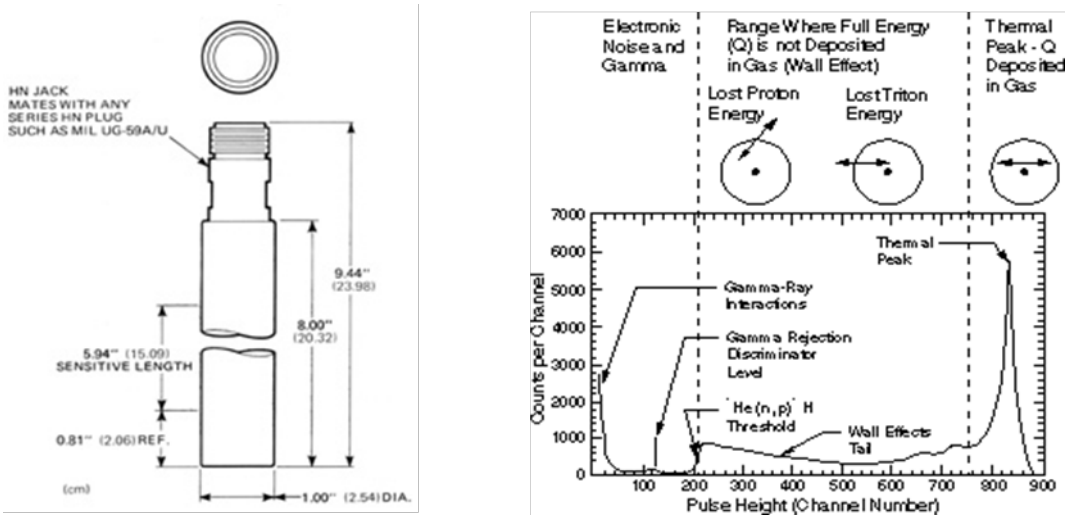

Figure 18: The 3He Proportional Counter: structure and typical pulse height spectrum.

4.5.1.3 The BF_3 Proportional Counter

This detector uses the nuclear reaction $^{10}B(n,\alpha)^{7}Li$ to detect thermal neutrons. The gamma rejection capability is higher than that of ^{3}He. On the contrary, the neutron detection efficiency is lower as compared to that of ^{3}He, because of the lower ^{10}B reaction cross section at thermal neutron energies. Additionally, boron fluoride is a poisonous gas, subject to transportation restrictions and for this reason it has not been used in safeguards and security applications [22].

4.5.1.4 Boron-lined Proportional Counter

In order to exploit the advantages of ^{10}B-based proportional counters (direct physical replacement of ^{3}He tubes and excellent rejection capabilities) without the use of a hazardous detection media, boron-lined gas-filled proportional counters have been proposed by Reuter-Stokes [23], Centronis [24] and Photonics [25]. These are gas-filled tubes whose inner surface is coated by a thin layer of ^{10}B-containing material. The only disadvantage is the relatively low detection efficiency; a boron-lined proportional counter has an efficiency approximately 7-times lower than a ^{3}He counter of the same size. This is due to the combination of two factors: the lower neutron absorption cross-section of boron and the solid nature of the absorber that limits the effective volume to very thin micrometric layers. Increasing the thickness of the coating layer is not an option to increase the detection efficiency, since it will limit the charged particle collection in the gas. An increase of efficiency has been recently achieved by increasing the surface of the coating, by using a bundle of thin tubelets contained within a tube.

4.5.1.5 Fission Chamber

The structure of a fission chamber is quite similar to that of a boron-lined proportional counter, only that the liner inside the tube is made of ^{235}U. The cross section of uranium is smaller than that of boron and therefore the neutron detection efficiency of fission chamber is smaller than any other proportional counter described above. This makes fission chamber particularly suitable for applications where too high neutron fluxes risk to overcharge the detector, for example in the measurement of spent nuclear fuel.

4.5.2 Detectors Based on Scintillators

Scintillator detectors are well known for their gamma detection capabilities as described in chapter 2. More recently, liquid and plastic scintillators that are also sensitive to neutron radiation have been introduced for safeguards applications Ejlien [26], Saint Gobain [27], Scionix [28]. These detectors contain low-Z elements such as hydrogen, and the neutron detection principle is based on the detection of the low-Z or proton recoil atom following an elastic scattering with a highly energetic neutron. The recoil detection principle makes these detectors sensitive only to fast neutrons, with the advantage that the incoming neutron energy information is preserved, thus providing neutron spectroscopic capabilities. Heterogeneous detectors, built by coupling plastic scintillators with liners of neutron absorbers such as Cadmium, Gadolinium or Lithium, are also available and allow simultaneous detection of fast and thermal neutrons ([26], [27], [29], [30] and [31]).

Since scintillators detect all ionising radiation, it is necessary to be able to discriminate between particle species/types. The classical discrimination technique is based on pulse shape. The dynamics of charge collection in the detector depends on the properties of the ionising particle: photons generate electric pulses with less pronounced tails than neutrons, so by analysing the shape of measured pulses it is possible to identify the particle. This technique is called pulse shape discrimination (PSD) and requires very fast digitisation (every 2ns) of each pulse's amplitude to calculate the ratio of the tail to the peak energy deposition that allows for particle discrimination [32].

Scintillators have high detection efficiency for fast neutrons, however the PSD technique does not offer perfect neutron/γ discrimination, meaning that there is an unavoidable rate of γ events which are misinterpreted as neutron events. Increasing the discrimination level may decrease the rate of misclassified γ events, but as a consequence the detection efficiency will also decrease.

Finally, it is worth mentioning a novel type of detector composed by tubes of high pressure (120 bar) ^{4}He gas, which acts as a scintillator for fast neutrons [33]. The detection principle is the same as in liquid scintillators, meaning that the neutron energy is transferred to the ^{4}He atoms by elastic and inelastic scattering, generating recoil α particles which, on their turn, generate the scintillation light. Despite the high pressure of the gas, the charge density of the detection media is still low enough to make the detector relatively insensitive to γ radiation.

4.6 Neutron Detection Electronics

4.6.1 The Neutron Pulse Stream and Rossi-α Distribution

Logical signals from either the amplifiers (for proportional counters) or from the digitisers/PSD algorithm (for scintillators) are passively summed or actively mixed using a derandomiser buffer in order to provide a stream of electronic pulses, each representing one detected neutron, to the input of the coincidence circuit. The pulse stream contains some combination of spontaneous fission, induced fission, (α,n) neutrons, and external background events. Using this pulse stream, it is necessary to separate out the correlated neutron events that are the quantitative signature for plutonium from the background of uncorrelated neutron events. It is not possible to distinguish individual neutrons, the order of neutrons in coincidences, or which individual neutrons are fission coincidences and which are (α,n) neutrons [34].

The Rossi-α distribution, developed for reactor noise analysis, is the distribution in time of events that follow after an arbitrarily chosen starting event. If only random, uncorrelated events are being detected, the distribution is on the average constant in time. If correlated events from fission are also present, then the Rossi-α distribution is given by:

$$N(t) = A + \mathrm{Re}^{-\frac{t}{\tau}} \qquad \text{(Eq. 11)}$$

where N(t) is the height of the distribution at time t, A is the accidental or random count rate, and R is the real or correlated count rate.

Figure ***19*** is a histogram of the Rossi-α distribution.

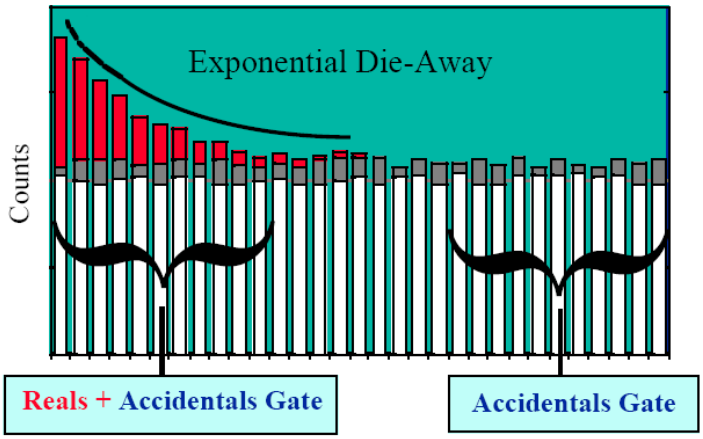

Figure 19: Histogram of a Rossi-a distribution. An actual measured distribution with exponential die-away time is superimposed above the histogram, and the (Reals + Accidentals) and (Accidentals) coincidence counting gates are superimposed at the bottom of the histogram [34].

The initial trigger events at t=0 can be either correlated or uncorrelated events. The red bars represent fission neutrons correlated to the initial pulse (Reals). The grey bars are neutrons from fissions that are not correlated to the initial event, either because the initial event was a random neutron or because it was from a different fission. The white bars are uncorrelated background neutrons, or neutrons from fissions where only a single neutron was detected. Note that the accidental rate A contains both of these component.

Figure ***19*** also shows two coincidence counting intervals superimposed, the R + A (Reals plus Accidentals) and A (Accidentals only).

4.6.2 Conventional Shift Register Basics

The goal of the conventional coincidence shift register circuit is to separate the incoming neutron pulse stream into correlated and uncorrelated events, and thereby provide a quantitative measure of a sample's fission rate. All neutrons are "remembered" by the shift register, enabling it to collect all possible neutron pairs in an inherently dead time-free manner. This is done by storing all incoming pulses for a predetermined coincidence interval, the gate width G, in an integrated circuit called a shift register. The circuit consists of a series of clock-driven flip-flops linked together in stages. Operation of the shift register coincidence circuit can be visualised in terms of the Rossi-α distribution shown in. It shows a prompt gate of width G that opens after the pre-delay PD and that collects real and accidental coincidences. After a delay much longer than the neutron die-away in the detector, another gate is opened that collects only accidental events. The difference between the counts collected in the R+A gate and those collected in the A gate is the desired real signal R (or that fraction of R that lies within the gate width G).

4.6.3 Multiplicity Shift Register Basics

There is more information in a neutron pulse stream that just single and double neutron events. In multiplicity counting the distributions of 0s, 1s, 2s, 3s, etc. in the coincidence gates are analysed to deduce the multiplicity distribution of the neutron events. Special multiplicity electronics are required to measure the neutron multiplicity distributions in the R+A and A coincidence gates. The multiplicity measurement records the number of times each multiplicity occurs in the coincidence gates.

4.7 Passive Neutron Coincidence Counting

The passive neutron coincidence counting is the most widely applied NDA safeguards method for the determination of the mass of bulk plutonium samples. The method detects the fast neutrons emitted as a result of spontaneous fission decays taking place in the sample. By analysis of the distribution of neutron detection in time intervals (coincidence gates) the rate of detected neutron pairs can be determined. The pair's rate is proportional to the plutonium mass.

The principal advantages of this assay are:

- ✓ Instrumentation is compact, relatively inexpensive, and easy to assemble and operate.

- ✓ Analysis procedures are well documented and internationally recognised. Modern software packages guide the user through the process of calibration, data acquisition, data analysis and interpretation.
- ✓ Accuracy below 1% are achieved when the reference samples are representative of the samples to be verified in terms of mass, chemical form, shape and containment.
- ✓ Short measurement times of typically 5 to 10 minutes are sufficient to achieve a precision below 1%.

4.7.1 Objective of the Technique

Passive Neutron Coincidence Counting (**PNCC**) is a technique for determining (in combination with the knowledge of isotopic ratios) the mass of plutonium in unknown samples. PNCC is the most used NDA technique for Pu assay, being applied to a large variety of sample types: solid samples, liquid ones (less frequently), powder, metallic, pellets, fuel elements, waste drums, etc.

4.7.2 Principle of Measurement/Definition of the Physical Principle

The measurement of plutonium by passive neutron coincidence counting makes use of the fact that plutonium isotopes with even mass number (238, 240, 242) show a relatively high neutron emission rate from spontaneous fission. These neutrons are emitted simultaneously and are therefore correlated in time. The count-rate of time-correlated neutrons is therefore a (complex) function of the Pu mass.

The detection of pulse-trains of time-correlated neutrons uniquely identify spontaneous fission events among other neutron sources emitting neutrons which are randomly distributed in time, such as (α,n) neutrons: this gives the possibility to determine the amount of plutonium in a sample. The isotope ^{240}Pu usually dominates the overall emission of spontaneous fission neutrons: ^{238}Pu and ^{242}Pu have comparable specific emissions (see Table 7) but, in reactor-grade plutonium, their abundance is much lower.

Since it is impossible to distinguish from which Pu isotope a detected neutron is originated, a commonly determined quantity in passive neutron coincidence counting is the effective ^{240}Pu mass (m_{240eff}). m_{240eff} represents a weighted sum of masses of the three isotopes ^{238}Pu, ^{240}Pu and ^{242}Pu:

$$m_{240eff} = a \cdot m_{238} + m_{240} + c \cdot m_{242}. \qquad \text{(Eq. 18)}$$

The coefficients a and c are the contributions of ^{238}Pu and ^{242}Pu to the neutron coincidence response in terms of an equivalent amount of ^{240}Pu. These coefficients give the relative contribution of the different isotopes to the spontaneous fission and can be calculated using the specific spontaneous fission yields from Table 7 and the abundance isotopic ratios Ri (i = 238, 240, 242) therefore the Pu isotopic composition needs to be known a-priori. For the conversion of m_{240eff} into the total amount of plutonium, m_{Pu}, the isotopic mass fractions R_{238}, R_{240} and R_{242} of the plutonium isotopes 238, 240 and 242 must be known (through γ- or mass-spectrometry) to calculate the isotope-specific quantity

$$^{240}Pu_{eff} = a \cdot R_{238} + R_{240} + c \cdot R_{242}. \qquad \text{(Eq. 19)}$$

The total amount of Pu is then evaluated as:

(Eq. 20)

$$m_{Pu} = \frac{m_{240eff}}{^{240}Pu_{eff}}.$$

Table 7: Spontaneous fission neutron yields.

Isotope	Spontaneous fission yield (neutrons/s.g)
^{238}Pu	$2.59\ 10^{3}$
^{239}Pu	$2.18\ 10^{-2}$
^{240}Pu	$1.02\ 10^{3}$
^{241}Pu	$5.0\ 10^{-2}$
^{242}Pu	$1.72\ 10^{3}$

4.7.3 Measurement Technique / Description of the Implemented Technique

The spontaneous fission neutrons emitted by a Pu-bearing sample have an average energy of about 2 MeV. They are slowed down to thermal energies and detected with ^{3}He tubes, which are the standard neutron detectors. In practice all passive neutron coincidence counters (PNCC) systems are equipped with neutron moderating assemblies, built from moderating materials such as polyethylene, in which the ^{3}He tubes are embedded, in order to increase the detection efficiency. A high detection efficiency (provided also by large number of detectors) is important for coincidence counting, because it reduces the counting time and provides higher precision.

The most common hardware used in the PNCC systems for the extraction of simple coincidence rate ("doubles") from the pulse train produced by the ^{3}He detectors, is the 'Shift Register Analyser'. It represents a good choice for the measurement of smaller amounts of well-characterised product materials like Pu-metal or Pu-oxide exhibiting small and predictable neutron multiplication effects [35] as well as low and predictable (α,n) production rates. For impure or inhomogeneous materials, such as scraps or waste, however, where corrections for multiplication, matrix and other effects become significant, the experimental information provided by the SR are not sufficient for a reliable and accurate Pu assay.

Passive neutron multiplicity counting technique (PNMC) has then been developed and it is increasingly applied in recent years [34]-[36], which provides an enlarged experimental information of 3 measured quantities: Singles, Doubles and Triples, which are the first three factorial moments of the counting rate. This allows extracting quantitative information on existing neutron multiplication effects from the measurement data.

With respect to conventional PNCC, PNMC allows to measure with better accuracy heterogeneous and poorly characterised materials and has the advantage that calibration does not require fully representative materials (i.e. multiplicity counters can be calibrated with standards completely different from the samples to be measured). The main disadvantage is the requirement of longer measurement time (or alternately higher detector efficiency) to get the necessary statistical precision on the Triples rate.

4.7.4 Performance Values for Passive Neutron Measurements

PNCC is applicable to practically all kinds of Pu-bearing materials, but the majority of the measurements for nuclear safeguards purposes are carried out on relatively pure and well characterised materials, such as, Pu-oxides and MOX materials (Pu-metal also, to a lesser extent). The amount of plutonium contained in this type of samples can typically range from the gram level up to several kilograms/sample. A second type of items falling into the category of product materials includes finished physical products like individual MOX fuel pins up to complete MOX fuel assemblies. Accordingly, a large variety of different neutron coincidence detection heads have been designed and optimised for the respective applications.

The major error sources contributing to the overall uncertainty are:

- Counting statistics, which is a random component
- Calibration parameters and uncertainties in reference materials (systematic)
- Correction for multiplication effects, dead time, (α,n) neutron emission (systematic)
- Nuclear data.

The Department of Safeguards of IAEA periodically reports on uncertainties to be considered in judging the reliability of analytical methods. Such reference uncertainties are called International Target Values for Measurement Uncertainties in Safeguarding Nuclear Materials (ITVs) and the latest revision was published in 2010 [21]. Table 8 presents ITVs random (r) and systematic (s) uncertainty components for passive neutron counting of the most significant nuclear materials. Table 9 gives the corresponding performance values for "impure" materials.

The High Level Neutron Coincidence Counter (HLNCC) is the industry standard neutron well Coincidence Counter (detector) developed at LANL for measuring plutonium in cans and small packages (Figure 20). A new upgraded version of the HLNCC has been designed and fabricated. The detector contains 18 ^{3}He tubes in a cylindrical polyethylene body. The vertical extent of the uniform efficiency counting zone is three times longer than that of the original unit without an increase in size or weight. A primary design goal for the HLNCC-II was to obtain a uniform or flat counting response profile over the height of the sample cavity while still maintaining a portable system. This was achieved by placing rings of polyethylene as 'shims" at the top and bottom of the detector to compensate for leakage of neutrons from the ends. In addition to these outside rings, the interior end plugs were designed to increase the counting efficiency at each end. The end plugs were constructed of polyethylene with aluminium cores to give a better response than plugs made of either material alone would give. Also, the sample cavity has a cadmium liner to prevent thermal neutrons from reflecting back into the sample and inducing additional fissions. Because the cadmium liner does not extend into the region of the end plugs, the polyethylene in the walls of the end plugs becomes an integral part of the moderator material for the ^{3}He tubes.

Figure 20: "Los Alamos" High Level Neutron Coincidence Counter (HLNCC).

Table 8: Performance values for m_{240eff} measured in thermal passive neutron coincidence counters with shift registers [21].

Method	**Material**	**Uncertainty Component (%rel)**		**ITV (%rel)**
		u(r)	u(s)	
HLNCC (High Level Neutron Coincidence Counter)	Pu Oxide	1	0.5	1.1
	MOX (>10% Pu)	2	0.5	2.1
	MOX (<10% Pu)	4	1.5	4.3
	MOX (Clean scrap)	5	2	5.4
	MOX Rods	2	1	2.2
	FBR MOX Assemblies	2	1	2.2

Table 9: Performance values for m_{240eff} measured in thermal neutron multiplicity counting mode [21].

Method	**Material**	**Uncertainty Component (%rel)**		**ITV (%rel)**
		u(r)	u(s)	
PSMR	Pu Oxide	1	0.5	1.1

(Plutonium Scrap Multicity Counter)	MOX (Clean scrap)	4	1	4.1
	MOX (Dirty scrap)	5	1	5.1

4.8 Neutron Multiplicity Counting

This method is an extension to the conventional coincidence counting method. In addition to the neutron count rate the "Doubles" (or "Reals") rate (correlated pair rate) also the "Triples" or triplet rate (correlated triplet rate) is determined. Multiplicity counting is used to determine the mass of plutonium of bulk samples where characteristics of the sample and the containment are unknown or not trustworthy. Also Pu containing waste is assayed using multiplicity counting in order to overcome the effects of the waste matrix and the unknown spatial distribution of the neutron source.

The principal advantages of neutron multiplicity counting are:

- The Pu mass is determined without the need for calibration with representative reference samples.
- The method does not rely on operator declarations of, for example, isotopic composition, chemical form, or container and matrix materials.
- The method incorporates a "very high degree of verification" as two additional sample parameters are determined together with the Pu mass. Instrumentation is compact, easy to assemble and operate.

4.8.1 The Calibration Procedures of Neutron Multiplicity Counters

The calibration procedure for neutron multiplicity counters does not require a series of representative physical standards to determine a curve of instrument response versus ^{240}Pu effective mass, as in the case of a coincident counter. Instead, the Singles, Doubles and Triples equations (Eqs. 21a/b/c) are solved directly for multiplication (M), α, and effective ^{240}Pu mass. To the extent that the plutonium samples satisfy the assumptions of the "point model", the measured Singles, Doubles, and Triples rates will correctly determine these unknowns without a calibration curve.

Using Eqs. 21a/b/c that relate S, D, and T to the unknown parameters, and obtaining S, D, and T from the multiplicity shift register, we have all the relationships needed for multiplicity analysis.

$$S = F\varepsilon M\nu_{s1}(1+\alpha)$$
$$D = \frac{F\varepsilon^2 f_d M^2}{2}\left[\nu_{s2} + \left(\frac{M-1}{\nu_{i1}-1}\right)\nu_{s1}(1+\alpha)\nu_{i2}\right] \qquad \text{(Eq. 21a/b/c)}$$
$$T = \frac{F\varepsilon^3 f_t M^3}{6}\left[\nu_{s3} + \left(\frac{M-1}{\nu_{i1}-1}\right)\left[3\nu_{s2}\nu_{i2} + \nu_{s1}(1+\alpha)\nu_{i3}\right] + 3\left(\frac{M-1}{\nu_{i1}-1}\right)^2 \nu_{s1}(1+\alpha){\nu_{i2}}^2\right]$$

Where:

F = spontaneous fission rate = 473 fission/s-g ^{240}Pu * m_{240}, where m_{240} = effective ^{240}Pu mass,
ν_{s1}, ν_{s2}, ν_{s3} = first, second and third moments of the spontaneous fission neutron multiplicity distribution,
ν_{i1}, ν_{i2}, ν_{i3} = first, second and third moments of the induced fission neutron multiplicity distribution.
ε = neutron detection efficiency,
M = sample self- multiplication,
α = (α,n) to spontaneous fission neutron ratio,
f_d = doubles gate fraction, f_t = triples gate fraction,

Note that some detected neutrons will not be counted inside the coincidence counting gate interval and this is reflected in the "gate fractions" f_d and f_t.

The system above can be solved obtaining the unknowns M, F and α, then m_{240} can be computed from F. To implement this procedure, it is necessary to supply the NCC code with several parameters that appear in the above-mentioned equations:

- ✓ The detector efficiency ε.
- ✓ The doubles gate fraction f_d.
- ✓ The triples gate fraction f_t.
- ✓ The nuclear data (ν).

The new SNMC is an advanced neutron multiplicity counter for the verification of inhomogeneous Pu samples, such as scrap material in MOX fuel fabrication plants (Figure 21). The innovative features of this counter with respect to existing ones rely on two aspects: (i) an optimised design based on Monte Carlo calculations in order to select the most appropriate materials, geometry and detector disposition for maximum efficiency and (ii) novel electronics based on DSP (digital signal processing) reducing the system dead time.

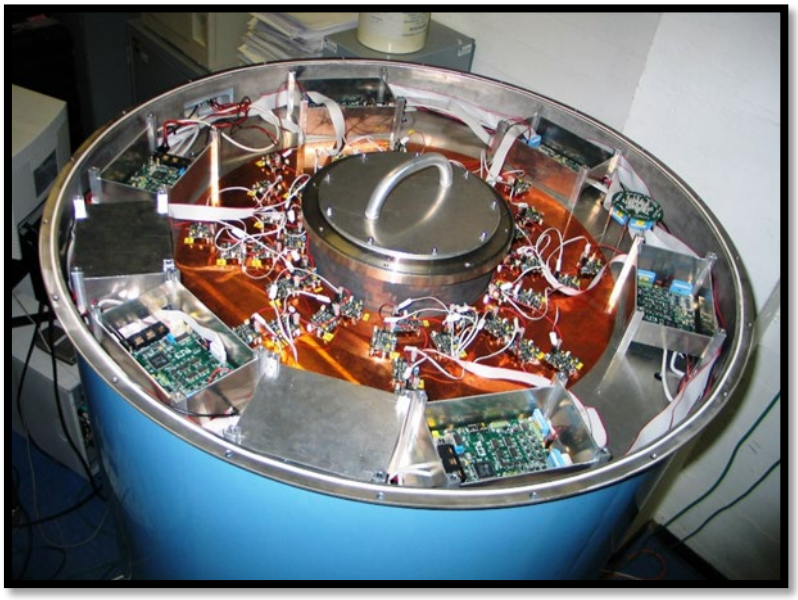

Figure 21: "Ispra" New Scrap Neutron Multiplicity Counter (SNMC).

4.9 Active Neutron Coincidence Counting

4.9.1 Objective of the Technique

Active Neutron Coincidence Counting (ANCC) is a technique for determining the mass of ^{235}U in Uranium-bearing samples with any enrichment (from LEU to HEU) in most of the usual physical forms: powder, metal, pellets, fuel elements, waste drums, etc.

4.9.2 Principle of Measurement/Definition of the Physical Principle

Due to the very low spontaneous fission yields of all uranium isotopes, passive neutron coincidence techniques are generally not suitable for the assay of uranium bearing samples (an exception is the use of (α,n) reactions from ^{234}U in uranium fluoride or the use of spontaneous fission of ^{238}U in large size LEU oxide samples). However, the fissile content in a sample can be readily measured by adding an external interrogation neutron source. The neutrons from the interrogation source will induce fission in the fissile nuclei of the sample. Neutron induced fission (like spontaneous fission) results in the simultaneous emission of several prompt neutrons ($<\nu>=2.41$ for fission induced by thermal neutrons in ^{235}U). The coincidence counting technique allows the distinction between events with the emission of single or multiple prompt fission neutrons. This makes it possible to discriminate between neutrons from the primary interrogating source and those from fission induced in the sample, provided that the primary source generates randomly non-correlated single neutrons. Coincidence counters with a random interrogation source are known as Active Neutron Coincidence Counters.

Among the radioactive sources those based on (α,n) reactions are the best candidate for active neutron interrogation. A frequently used source is AmLi. The main advantage of the AmLi source with respect to other (α,n) reactions is the low energy of the emitted neutrons: the mean energy is 0.54 MeV, which minimises the probability of fast fission in ^{238}U.

For small samples the "Reals" coincidence rate is proportional to the quantity of fissile material in the sample. For large samples the self-shielding phenomena limit the "visibility" of fissile material to the interrogating neutrons, causing saturation effects in the response function and underestimation in the quantity of the fissile material (unless the calibration is designed to take the effect into account). This self-shielding effect is one of the major contributors to the systematic assay error of active neutron techniques.

4.9.3 Measurement Technique / Description of the Implemented Technique

Apart from the presence of the interrogating source, the methods and procedures of shift-register based instruments for active neutron coincidence counting are very similar to those used in PNCC counting.

There are basically two major families of instruments in this category:

- the Neutron Coincidence Collar (NCC) in active mode, and
- the Active Well Coincidence Counter (AWCC).

Neutron collars are typically composed of four slab detectors in a square arrangement, and are used for the assay of fresh fuel assemblies. Some models have a modular layout allowing the adjustment of collar dimensions to the fuel element size, others have fixed configurations for specific fuel type (PWR and BWR). Collars can be used both in passive and active mode. For passive only applications (MOX fuels) normally all the four sides are equipped with detectors, for active/passive applications (LEU fuels) only three detection slabs are used and the fourth wall hosts the source.

Active well coincidence counters are general-purpose devices for uranium bearing samples at practically any enrichment (HEU and LEU), chemical form (metal, oxide) and physical form (powders, pellets, plates, MTR elements). An AWCC is conceptually similar to a passive HLNCC except for the presence of two AmLi sources in the top and bottom polyethylene plugs.

A cadmium liner, typically 1 mm thick, can be added to the inside walls of the coincidence counter. The Cd absorbs the thermal neutron component from the interrogation flux (Cd cut-off at about 0.55 eV) with a twofold function:

- it improves the penetration of the neutron flux in the sample, therefore it is recommended to use it when analysing massive samples, and
- it reduces the perturbation due to burnable poison in fuel elements, and thus the need for specific correction factors which are highly sensitive on those fuel characteristics the inspectors need to verify, such as the ^{235}U enrichment.

When the Cd liner is in place, the system is defined as in "fast mode", whereas the configuration without Cd liner is called "thermal mode". However, the Cd cut-off absorbs the thermal neutron flux, which has the highest probability of inducing fissions in the ^{235}U atoms, impacting highly on the interrogation efficiency of the methods.

By extending the shift register electronics it is possible to operate ANCC systems in multiplicity mode. This is exactly analogous to the extension from PNCC to PNMC. Under certain conditions three unknown quantities can then be determined instead of just two. This allows, for example, a variable detection efficiency (perhaps due to variable moisture content) to be taken into account in the interpretation model. The use of multiplicity counting in ANCC systems is still undergoing development.

4.9.4 Performance Values for Active Neutron Measurements

Performance values for the assay of the fissile uranium content obtained with two traditional instruments based on ^{3}He proportional counters (NCC and AWCC) for different materials are given in Table 10 [21], [37], [38], The two components to the total uncertainty are split: random (r) and systematic (s). Note that these values assume that a representative calibration exists, for each material type quoted. The uncertainty for the fast mode assay is generally higher than for the thermal mode. Active neutron interrogation techniques can also be used for other purposes, for instance waste characterisation.

Table 10: Performance values for the determination of the ^{235}U mass loading in fresh LEU fuel elements (600 s counting time, fast operation mode) [21].

Method	Material	Uncertainty Component (%rel)		ITV (%rel)
		u(r)	u(s)	
AWCC (Active Well Coincidence Counter)	HEU Metal, Alloys	5	3	5.8
	HEU Fuel Elements	3	3	4.2
FRSC (Fuel Rod SCanner)	LEU Fuel Rods	1	1	1.4
UNCL (Uranium Neutron Coincidence	LEU Assemblies	4	2	4.5

Collar)	HEU Assemblies	1	1	1.4
HEPC (High-Efficiency Passive Counter)	LEU Items	3	1	3.2

The **Active Well Coincidence Counter (AWCC)** is a transportable high-efficiency counter for the measurement of both uranium and plutonium (Figure 22). Originally developed by the Los Alamos National Laboratory (LANL).

For uranium measurement the AWCC is used in **Active Mode**. Two americium-lithium neutron sources are inserted – one in the base and one in the plug unit – and the AWCC is operated in random driver mode. Uncorrelated neutrons produced by the Am-Li sources induce fission in ^{235}U samples in the measurement chamber. The coincidence counter electronics (Shift Register) can be used to determine to coincidence count rate, which is attributable to the induced fission in ^{235}U. Using this method, the mass of uranium is readily determined.

Two Action Modes are available depending on the size of the ^{235}U sample.

- The AWCC in **Thermal Active Mode** is most appropriate for measuring low-enriched uranium materials. In this mode the sleeve and end plug cadmium coverings are removed. The detection level in this mode is approximately 1 mg of ^{235}U.
- **Fast Active Mode** is employed for the measurement of highly enriched material such as uranium metal, uranium thorium fuel and LWR fuel pellets. In this mode the cadmium plates and sleeve are inserted and the detection limit is approximately 23 mg of ^{235}U.

Figure 22: Left: Active Well Coincidence Counter (AWCC). Right: Uranium Neutron Coincidence Collar (UNCC).

Since the first development of the UNCL, the nuclear industry has progressively introduced new commercial fuel designs with higher nominal ^{235}U linear mass loadings compensated by burnable neutron poison rods (typically Gadolinium). Burnable poisons are strong thermal neutron absorbers aiming to keep the reactivity of the fuel to a low controllable level despite higher initial enrichments. Their presence affects the rate of detected coincidence events, by decreasing both the thermal interrogating neutron flux and the rate of coincidence neutrons from induced fissions. Therefore, correction coefficients have been developed and applied to the verification measurement to account for such effect on the basis of the operator's declaration of the burnable poison content. For the typical ranges of Gadolinium content employed in commercial fuel elements, correction factors are in the order of tens of percent in "thermal mode" and only few percent in "fast mode" measurement, and proportional is their impact of the overall measurement uncertainty. However, "fast mode" with typical UNCL detectors is non-practical due to the low efficiency and consequently the long measurement times required. To give an example, the measurement time needed to achieve a 2% statistical uncertainty on the coincidence counts increases from few minutes to around 2 hours for the UNCL respectively in "thermal" and "fast" interrogation modes.

In the past decade, few alternative neutron coincidence collars have been developed to allow practical measurement of fresh fuel assemblies in "fast mode", thus reducing the impact of burnable poisons on the verification measurement of fresh fuel.

The **EURATOM Fast Collar** has been developed by LANL in collaboration with the European Commission's Safeguards Directorate in two designs for PWR and BWR, respectively called **EFCP** and **EFCB** [38]. The detectors employ ^{3}He proportional counters with higher pressures than the standard tubes (10 atm), providing high efficiency to thermal neutrons. The tubes are arranged in two rows within the polyethylene moderator, and the configuration of the rows is optimised to minimise the counts of uncorrelated neutrons from the AmLi interrogation source (i.e. the noise). Both detectors are currently routinely used in fast mode for safeguards verification by EC inspectors. A typical PWR verification can be made in a total time of 30 min with an uncertainty in the measured mass of 2% at one standard deviation (1σ). A BWR verification can be made 20 min with 1σ uncertainty in the measured mass of 2.5%.

The **Fast Neutron Collar (FNCL)** was developed by the IAEA in recent years ([39],[40]) and is about to be introduced as an authorised safeguards verification tool. The FNCL employs liquid scintillators that directly detect fast neutrons. The system only operates with a Cd-liner in "fast" interrogation mode to reduce sensitivity to Gadolinium. Since fast neutrons are measured without moderation, the detection time interval of coincident neutron occurs over time scales of the order of 10's of nanoseconds (three orders of magnitude lower than that of thermal neutrons detectors), and the random coincidence noise originating from the $^{241}AmLi$ source is quasi inexistent for the typical $^{241}AmLi$ sources used in active neutron counters. Additionally, functioning as a neutron spectrometer, energy thresholds are applied to prevent the detection of neutrons below about 0.5 MeV, which minimises the response of the FNCL to $^{241}AmLi$ source neutrons and further de-sensitises the system to the influence of Gadolinium (lower energy fission neutrons have a higher chance of being captured by Gadolinium when scattering in the fuel). This also opens the possibility to use such a system with stronger interrogation sources and hence reduce even further the required measurement times.

The FNCL design, shown in Figure 23 is based upon 12 EJ-309 fast neutron liquid scintillators configured in three detector panels (four each). This forms three sides of the measurement cavity. The fourth side is a source panel specific to the type of FFA being measured (PWR, BWR or VVER- 1000). Each source panel holds two $^{241}AmLi$ sources for active interrogation. The 12 detector channels are fed into a compact all-in-one Data Acquisition System (DAQ) where the collected signals are digitised using 500 MHz 14-bit digitilisers and all

resulting signal wave forms, sampled over 256 ns, are recorded with respective time stamp and detector address.

Experiments have shown that the FNCL is able to provide verifications with less than 1% relative uncertainty in the assayed mass (at 1 standard deviation) in a measurement time of only 15 minutes. Additionally, the reduced impact of Gadolinium burnable poison on the detected coincidence rate can be left un-corrected while still providing verification results within the ITVs, thus ensuring independence of the verification from the operator declaration [41].

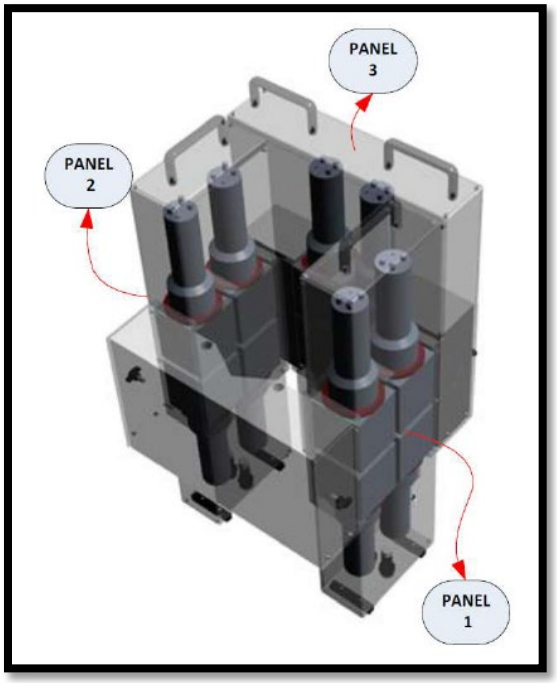

Figure 23: Illustration of the FNCL detector/source panel geometry.

The **Under Water Coincidence Counters (UWCC)** that has been designed for the measurement of plutonium in mixed oxide (MOX) fuel assemblies prior to irradiation (Figure 24). The UWCC uses high-efficiency ^{3}He neutron detectors to measure the spontaneous fission and induced-fission rates in the fuel assembly. Measurements can be made on MOX fuel assemblies in air or underwater. The neutron counting rate is analysed for singles, doubles, and triples time correlations to determine the $^{240}Pu_{effective}$ mass per unit length of the fuel assembly.

The UWCC system can verify the plutonium loading per unit length to a precision of less than 1% in a measurement time of 2 to 3 minutes.

The JRC began a collaboration with DG ENER (Euratom Safeguards) in 2000, to study a verification method for low enriched uranium (LEU) as a replacement of the traditional active interrogation with the PHONID device. A new measurement method, based on the detection of neutrons emitted after the spontaneous fission of ^{238}U, has been investigated. Feasibility of the method has been demonstrated through a campaign of measurements performed with an Active Well Coincidence Counter (AWCC) on PERLA LEU reference materials. The results showed that the real coincidence rate of measurements with a cadmium liner was a good indicator for ^{238}U mass. Therefore, a passive neutron assay, combined with gamma spectrometry to

measure the enrichment, can satisfy the verification requirements. The low neutron yield of ^{238}U requires a high efficiency detector to keep the counting time reasonably short. The JRC designed, built and characterised a first prototype of a **High Efficiency Passive Counter (HEPC)**. This prototype was tested with PERLA uranium reference materials and allowed us to validate the method and assess its accuracy to better than 1% (Figure 25). Two new detection systems for the DG ENER (Euratom Safeguards) inspectors at the Dessel (Germany) and Juzbado (Spain) fuel fabrication plants were commissioned in 2003.

Figure 24: Under Water Coincidence Counters - Model 2106 (UWCC).

Figure 25: The High Efficiency Passive Counter (HEPC).

5 Non-Destructive Assay Options for Nuclear Spent Fuel

This section is a summary of many techniques available as of 2013, for the NDA of spent nuclear fuel assemblies that are to be encapsulated in a deep geological repository, with a minor update to the gamma tomography subsection. For some instruments, further developments have taken place since 2013, but such efforts are not included in the description here (the interested readers is however encouraged to look for research publications to get a more recent update). The list of techniques is mostly repeated from reference [42] which aimed at listing NDA options available for the operator of an encapsulation facility in the context of deep geological disposal. Placing spent nuclear fuel in a difficult-to-access storage where re-verification of the fuel is not possible, puts additional requirement on the verification such as requirements related to partial defect verification. Hence, the Next Generation Safeguards Initiative (NGSI) spent fuel (SF) effort developed and studied measurement techniques to enhance the verification capability. Note that the list of techniques and instruments in this section does not make any distinction between instruments approved for use in Safeguards to those that are under development.

Several of the prototype instruments described here were developed within the NGSI effort and describe measurement techniques and instruments that were at the time under development. Some exist only in simulations space, while others were built and tested in the field. The list is however also complemented by other techniques, which were not in the NGSI SF effort (and are hence much more mature).

The measured signal and discussion of expected uncertainties are included. The description of each instrument is also complemented with information regarding requirements on measurement times and needed infrastructure.

5.1 ^{252}Cf Interrogation with Prompt Neutron Detection (CIPN)

What is measured? Prompt neutrons emitted at the end of an induced fission chain initiated by a ^{252}Cf source (or neutron generator) placed on the far side of the assembly from the detectors, as illustrated in Figure 26

What is quantified? Multiplication or fissile content (weighted sum of ^{235}U, ^{239}Pu, and ^{241}Pu); for fissile content to be determined, a neutron absorber correction is necessary. For thermal-induced prompt fission per unit mass, ^{239}Pu and ^{241}Pu produce ~1.5 and ~2.0 times as many neutrons as ^{235}U, respectively.

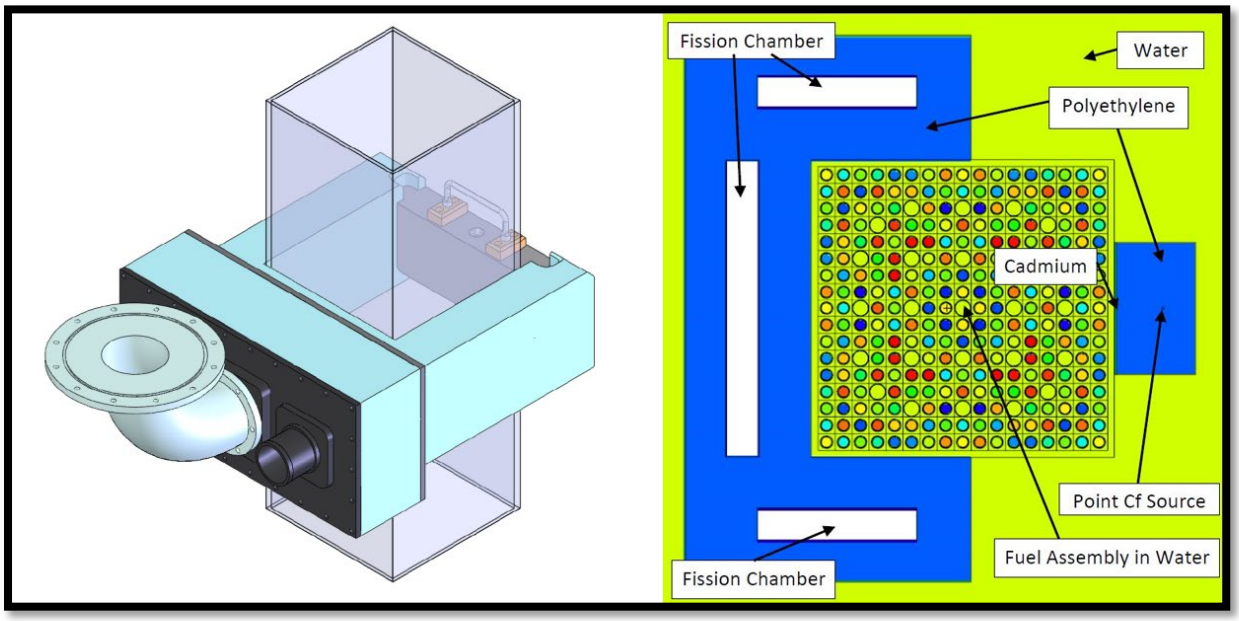

Figure 26: Left: Mechanical drawing of a CIPN instrument; supported on a pole, the californium source either is inserted in the removable door or is part of the removable door. Right: Conceptual design of CIPN instrument as simulated in MCNP for the NGSI Spent Fuel Project [43].

Description of the basic physics: Two measurements of the total neutron (TN) count rate are made with a detector that is very similar to a Fork Detector. For the first measurement, the ^{252}Cf source is located far from the assembly. This first measurement quantifies the passive neutron count rate. For the second measurement, the only change is that the ^{252}Cf source is brought in close to the assembly, ~5 cm from the center of one side of the assembly that is opposite the detector. This second measurement quantifies the combined count rate of the background and the neutrons that induced fission in the assembly. Given the size of the assembly and the dimensions of the detector, the probability of a ^{252}Cf source being directly detected is small. The net signal above the background overwhelmingly is due to the fission chain reaction that occurs across the assembly [43].

Expected measurement time: A ~100-s count duration will produce a statistical uncertainty of ~0.2% for a ~0.5-m section of the assembly. For the CIPN design used by the NGSI Spent Fuel Project [43], a CIPN signal that was ~75% stronger than the background (net count rate of ~1 × 104 counts/s) was produced with a 2 × 108 n/s ^{252}Cf source (100 μg) for a fully burned assembly (45 GWd/tU, 4% wt % ^{235}U, 5 years cooled). Note that the largest commercially available ^{252}Cf source is 50 times stronger than the source used here. A deuterium-tritium (DT) or a deuterium-deuterium (DD) generator could be used instead of a californium source [44].

5.2 Calorimetric Decay Heat (CDH)

Decay heat in nuclear fuel is defined as the heat produced within the fuel assembly as a result of radioactive decay.

What is measured? The temperature increase in water surrounding the fuel assembly, placed within a calorimeter.

What is quantified? The thermal power (energy per time unit) produced in the fuel assembly.

The basic of CDH technique consists of the following steps:

- Establish a calibration between temperature increase in the calorimeter and a well-known (electrical) power input to the volume within the calorimeter.
- Measure the temperature increase in the calorimeter with a nuclear fuel assembly that is positioned within the calorimeter. Use the calibration to estimate a decay heat value from the measured temperature increase.
- Correct the decay heat value for losses due to radiation that escapes from the calorimeter.

Expected measurement time: One calorimetric measurement of one fuel assembly takes on the order of 4–5 hours [45]. The measurement time is nearly the same for BWR and PWR assemblies.

5.3 Delayed Gamma-Ray Spectrometry (DGS)

What is measured? Photons emitted from fission products in the seconds to minutes following active interrogation of the assembly. The 3- to 6-MeV energy range is of primary interest [46]

What is quantified? Multiplication, fissile content (weighted sum of ^{235}U, ^{239}Pu, and ^{241}Pu), or relative masses of four main isotopes that fission. For fissile content to be determined, a neutron absorber correction is

necessary. The role of ^{238}U can be minimised by lowering the energy of the interrogating neutrons by both measuring in water and placing judiciously selected material between the neutron generator and the fuel.

Description of the basic physics: An active interrogation source such as a neutron generator or linear accelerator (LINAC) is used to produce neutrons for the purpose of inducing fission in the assembly, as illustrated in Figure 27 The fission products produced by induced fission are the source term for the DG measurement. The majority of the detectable DGs are emitted from fission products with half-lives in the 1.0- to 1000-s time interval [46]. The NGSI Spent Fuel Project researched the optimal combination of interrogation and count time; results to date indicate that the interrogation scheme selected for the 2011 Review Committee Report is a reasonable choice. In that report, a 15-minute interrogation, 1.0-minute cool down, 15.0-minute count time scheme was selected [46]. The ability of a DG measurement to discern among ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu is derived from the data depicted in Figure 28. This figure illustrates per fission what percentage of total fissions, for each of the four main isotopes, results in a particular fission product.

The basic concept for quantifying the relative mass of each isotope rests on detecting DG rays from several fission products so that the relative intensities of the emitted lines allow the separation of the relative contribution of each of the four major isotopes.

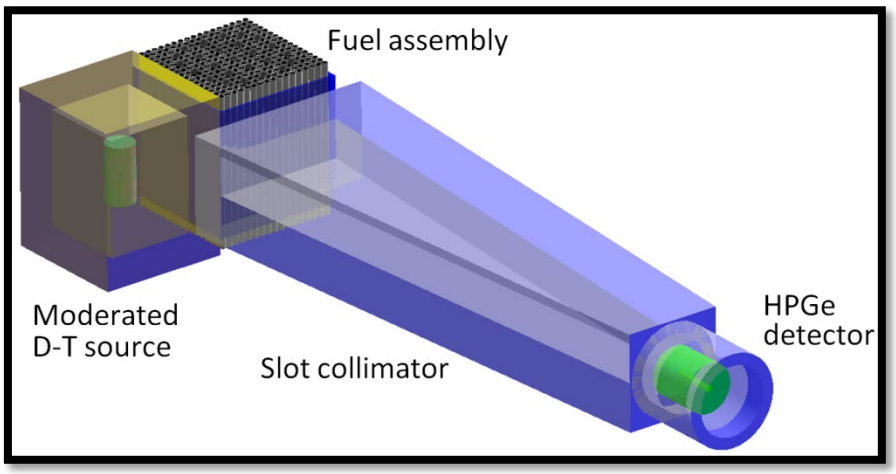

Figure 27: Conceptual design of DG instrument as simulated in MCNP for the NGSI Spent Fuel Project [46].

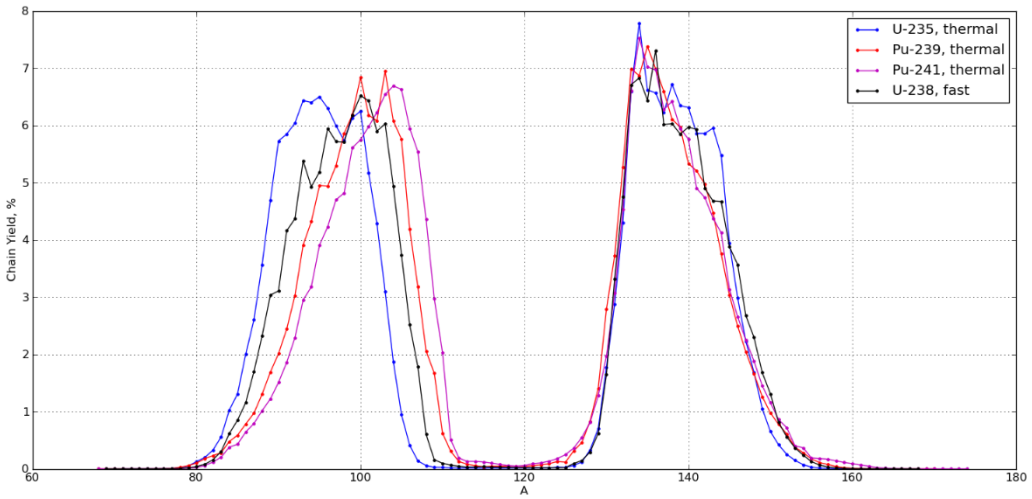

Figure 28: Illustration of the fission product yield per fission for each of the four main isotopes [46].

Expected Measurement time: The analysis approach is a point of active research; a rough approximation of the measurement time value is ~30 minutes for measuring a ~0.5-m section of the assembly with a 1×10^{12} DT neutron generator [46]. An average strength of ~1×10^{11} n/s is expected to be a lower limit to the neutron generator strength when ~10 detectors are used.

5.4 Delayed Neutrons (DNs)

What is measured? Neutrons emitted from fission products in the seconds to minutes following an active neutron generator burst.

What is quantified? Fissile content (weighted sum of ^{235}U, ^{239}Pu, and ^{241}Pu) emphasising the presence of ^{235}U.

Description of the basic physics: A neutron generator is used to produce neutrons for the purpose of inducing fission in the assembly, as depicted in Figure 29. The fission products are the source term for the DN emission. The majority of the detectable DNs are emitted from fission products with half-lives in the 2- to 22-s time interval [47]. The interrogation scheme selected for the 2011 Review Committee Report [47] used a 0.9-s interrogation interval, followed by a 0.1-s pause (for the burst neutrons to die away), followed by a 1.0-s DN count interval [47] he timing is flexible: faster or slower will work. The net DN count rate is the difference between the passive background count rate measurement made before interrogation and the DN count rate determined during active interrogation. The desired precision is obtained by repeating the interrogation/pause/count cycle.

In Table 11, the fission cross section (σ), DN fraction (β), and yield per fission (υ) are listed for the four main isotopes of relevance. This table emphasises the point that DNs preferentially measure ^{235}U relative to ^{239}Pu by a factor of ~2 per unit mass. Several of the other techniques have the opposite weighting; for prompt fission induced by thermal neutrons, per unit mass, ^{239}Pu produces ~1.5 times as many neutrons as ^{235}U and ^{241}Pu produces ~2.0 as many neutrons as ^{235}U.

Table 11 also indicates that ^{241}Pu and ^{238}U could be significant contributors. The role of ^{241}Pu is important but not dominant because the mass of ^{241}Pu is generally 4 to 10 times less than that of ^{235}U. The role of ^{238}U is minimised to a few percent by keeping the interrogation energy below ~1 MeV.

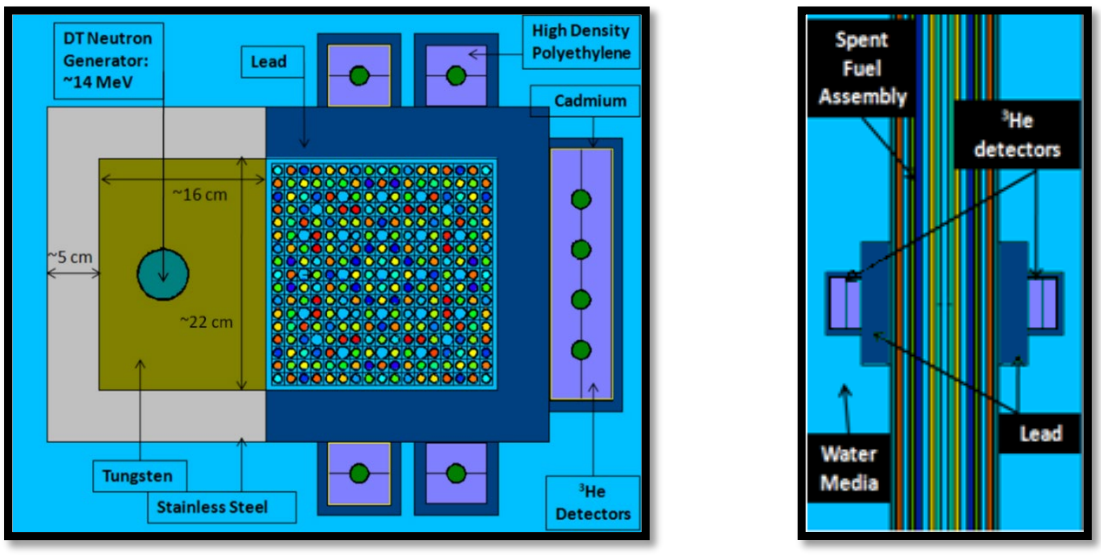

Figure 29: Conceptual design of the DN instrument as simulated in MCNP for the NGSI Spent Fuel Project [47].

Table 11: Fission Cross Section (σ), DN Fraction (b), and Yield per Fission (υ) for the Four Major Sources of DN. The Final Column Gives a Weighting of Each Isotope in the DN Signal on a Per Atom Basis [47].

Isotope	Fission Cross Section (barns)	DN Fraction as a Yield per Fission ($\beta\nu$, %)	$(\sigma\beta u)_{isotope}/(\sigma\beta u)^{239}_{Pu}$
^{235}U	584 (thermal)	1.65	2.03
^{239}Pu	742 (thermal)	0.64	1
^{241}Pu	1010 (thermal)	1.58	3.44
^{238}U	0.7 (~2 MeV)	4.39	6.86 (note: fast/thermal ratio)

Expected measurement time: For the ^{3}He design used by the NGSI Spent Fuel Project, a fully burned assembly (45 GWd/tU, 4 wt % ^{235}U, 5 years cooled) produced a net DN signal of ~5 × 105 counts/s, with a background signal of ~15 × 10^{5} counts/s for a neutron generator that produced 1 × 10^{11} n/s [47]. For such a setup, only ~1 s is needed to obtain less than 1% statistical uncertainty.

5.5 Differential Die-Away (DDA)

What is measured: Traditional DDA measured the prompt neutrons emitted by induced fission during a time interval when the active generated interrogating neutrons were thermal in energy. The NGSI Spent Fuel Report [48] produced for the NGSI Review Committee implemented traditional DDA for which the count interval started 200 μs after the burst ended so that the thermal neutrons from the burst would be ~1% of the neutrons produced by induced fission. The updated DDA reports by the NGSI Project [48], expanded the scope of the DDA research by looking at the signal at times between the termination of the burst and 200 μs. These recent results are still being called DDA, although strictly speaking the research has strayed from the traditional mode of counting the TN count rate only when thermal neutrons are remaining in the sample of interest.

What is quantified: Multiplication and fissile content (weighted sum of ^{235}U, ^{239}Pu, and ^{241}Pu) emphasising the presence of ^{239}Pu and ^{241}Pu. For prompt fission induced by thermal neutrons, per unit mass, ^{239}Pu and ^{241}Pu produces ~1.5 and ~2.0 times as many neutrons as ^{235}U, respectively.

Description of the basic physics: A measurement begins with the burst of neutrons (~10 μs in duration was used for the NGSI research) produced by a neutron generator, as illustrated in Figure 29; note the DN setup was used for DDA in the NGSI Project. A DD (2.2-MeV) or DT (14-MeV) generator would work. Those burst neutrons slow down to near thermal energies (0.025 eV). Because the cadmium-covered detectors detect neutrons only above ~0.5 eV, for the NGSI setup with ^{238}U and oxygen in the fuel, after ~200 μs the detected count rate for the burst neutrons is low. Subsequent simulations indicated that the count rate of the burst neutrons was ~1% of the count rate from a fully burned assembly at 200 μs [47]. Note that even though the direct count rate from the burst neutrons is very low, the burst neutrons are still present in the fuel as thermal neutrons—they are just very unlikely to penetrate the cadmium and thus are very unlikely to produce a count. If fissile material is present in the fuel, induced fission by thermal neutrons will occur and neutrons will be produced with much higher energy (~2 MeV on average). Some of the induced fission neutrons will have energies above the cadmium cut-off energy when they arrive at the detector and will be detected. Traditional DDA functions by detecting neutrons during a time window when the burst neutrons are negligible

compared with the induced fission count rate; recent research has indicated benefits of measuring sooner after the burst [49]. Because the DDA involves interrogating the fuel with thermal neutrons, a logical concern is self-shielding. However, because a fully burned assembly is significant multiplying, the entire fuel assembly is interrogated.

Expected measurement time: A few seconds count time is expected for a 0.5-m section of the assembly. For the ^{3}He design used by the NGSI Spent Fuel Project, a DDA signal (0.2- to 1.0-ms integration window) that was ~50% stronger than the background was produced with a 5×10^{8} n/s neutron generator (10-μs burst, 100-Hz repetition rate) for a fully burned assembly (45 GWd/tU, 4 wt %, ^{235}U, 5 years cooled). Because the background for such an assembly is $\sim 15 \times 10^{5}$ counts/s, excellent statistics are obtained in a second. Recent results indicate that an uncooled neutron generator of $\sim 1 \times 10^{8}$ n/s will suffice.

5.6 Differential Die-Away Self-Interrogation (DDSI)

What is measured: The time and tube location at which each neutron is detected, with an accuracy of ~0.1 μs. Singles and doubles count rates are calculated from this raw data.

What is quantified: Multiplication or fissile content (weighted sum of ^{235}U, ^{239}Pu, and ^{241}Pu); for fissile content to be determined, a neutron absorber correction is necessary. For thermally induced prompt fission per unit mass, ^{239}Pu and ^{241}Pu produce ~1.5 and ~2.0 times as many neutrons as ^{235}U, respectively.

Description of the basic physics: Two possible designs of a DDSI detector are depicted in Figure 30. Traditional DDA begins with a neutron generator burst; the burst neutrons interrogate the sample, and data are collected only after the burst neutrons have become thermal in the sample. DDSI has DDA in its name because DDSI also has a burst; however, in the case of DDSI, the burst is a spontaneous or induced fission event that liberates nubar neutrons. DDSI has two signals of interest in the context of spent fuel. One signal uses the ratio of the count in an early time gate to the counts in a late time gate. The other signal uses the ratio of the doubles count rate in the late gate to the singles count rate (D/S) [50]. The D/S ratio is a standard quantity used in classical coincidence counting. What makes the DDSI doubles calculation unique is the use of a very long delay between the measurement of a neutron trigger and the opening of the gate [50]. In traditional coincidence counting, an integration interval in time, a gate, is opened as soon after the detected trigger neutron is detected as possible within the limits of the electrical system. With DDSI the gate is delayed for the purpose of separating the passive interrogating signal, composed primarily of ^{244}Cm, from a signal that is primarily induced fission. The first induced fission, in a chain of induced fissions, is delayed in time by ~10 μs from the time when the initiating neutron was born. This delay is approximately the time required for the neutron that initiates a fission to thermalise. Note that in spent fuel, ~80% of induced fissions occur at thermal energies. Given that the multiplication in a fully spent assembly is ~2, a series of induced fissions is common and the induced fission signal can be largely separated from the initiating burst event (often a ^{244}Cm fission).

Expected measurement time: The measurement time for the doubles dictates the overall measurement time. For a 45-GWd/tU, 4 wt %, ^{235}U, 5-years-cooled assembly, a statistical uncertainty of 1% for the doubles can be obtained in 2 minutes for a 20-μs pre-delay and a 32-μs gate width. For this same assembly with a 60-μs pre-delay and a 32-μs gate width, it takes 16 minutes to obtain the same uncertainty. By changing the pre-delay from 20 to 60 μs, the sensitivity doubled for a change in the fissile content, but the count time increased by a factor of 8 [50].

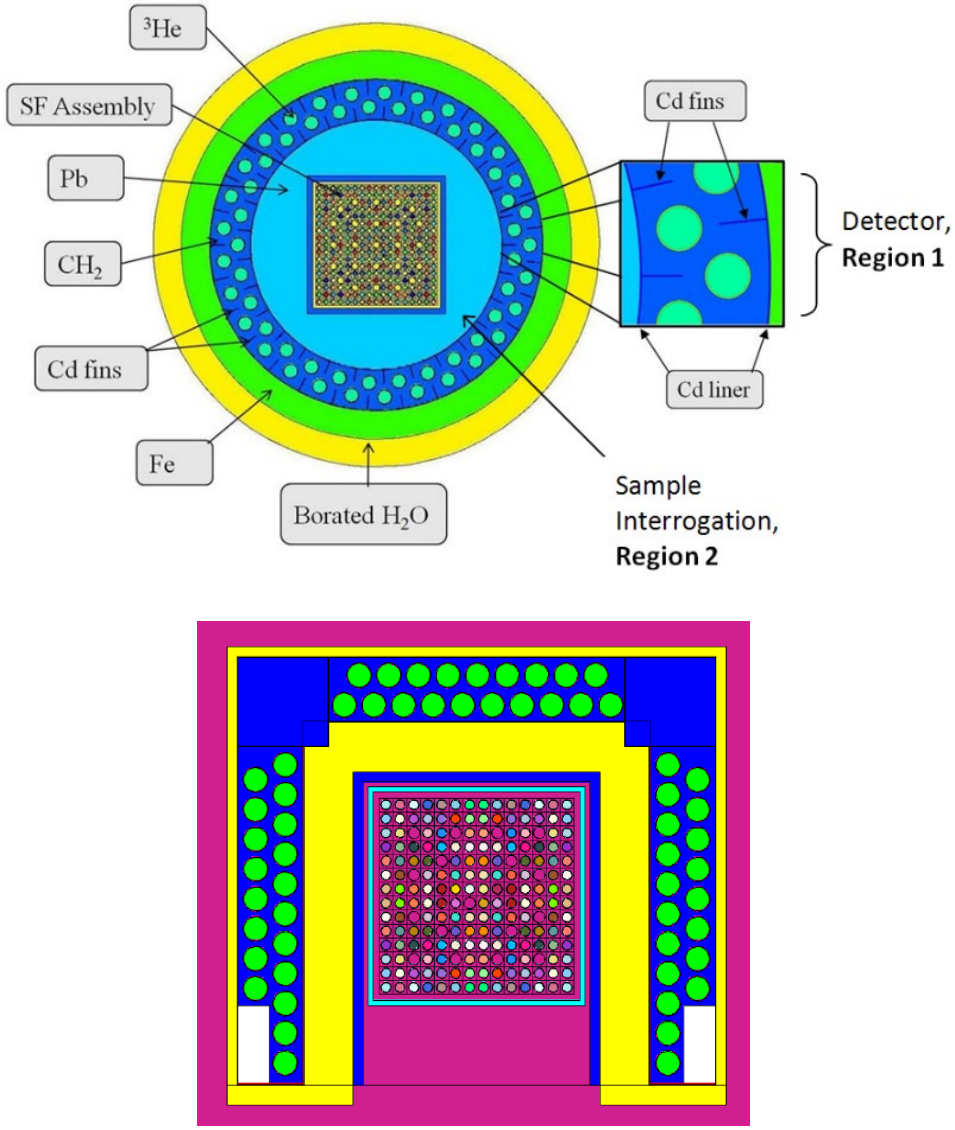

Figure 30: Up: Conceptual design of DDSI instrument as simulated in MCNP for the NGSI Spent Fuel Project [50]. Down: Modified DDSI design to enable fuel to be loaded from the side.

5.7 Cerenkov Viewing Devices

What is measured: The Cherenkov (ultraviolet) light produced in water by beta and gamma radiation escaping a fuel assembly [51]

What is quantified: Two-dimensional image of Cerenkov photon intensity are acquired for safeguards identifications of partial or gross defect in fuel assemblies. The device is used to identify an assembly with gross or partial defects.

Description of the basic physics: When the gamma radiation from the fuel assembly is absorbed in the surrounding water of a storage pool or of reactor, recoil electrons are produced, with a velocity exceeding the speed of light, and therefore lose energy by emitting Cherenkov light. The Cherenkov viewing devices are optimised to view the ultraviolet light produced in the water surrounding a fuel assembly. The two mean Cerenkov devices are the Improved Cerenkov Viewing Device (ICVD) (see Figure 31) and the Digital Cherenkov Viewing Device (DCVD) (see Figure 32). The glow of the Cherenkov light is bright in the regions close to present fuel rods, i.e. in the adjacent water in e.g. water channels. Figure 33 shows a picture of a DCVD). The

DVCD camera is used to verify assemblies with long cooling times and/or low burnups, which have weak Cerenkov signals that cannot be seen with a standard handheld ICVD [52].

Expected measurement time: The DCVD is a camera, so one image is collected within 1–2 s. The image is saved for offline analysis. Reference [52] reported that verification of 12 fuel assemblies was performed in 82 minutes.

Figure 31: A handheld Cerenkov Viewing Device (ICVD).

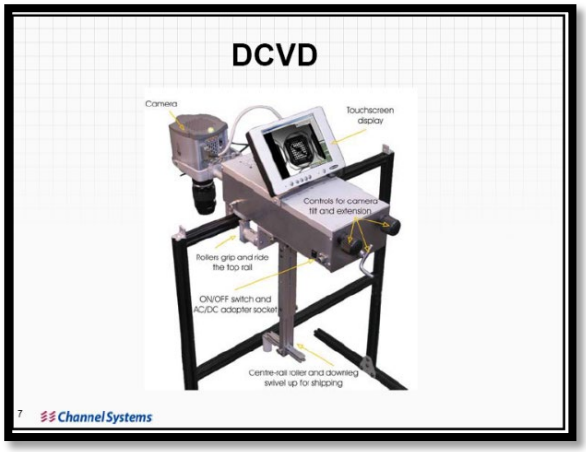

Figure 32: Main parts of a DCVD acquisition system.

Figure 33: A DCVD mounted above a fuel storage pool.

5.8 Gamma Tomography (GT)

What is measured: The two-dimensional (2D) intensity distribution of gamma radiation of one or more energies at one axial level of the fuel assembly. The distribution is measured over many lateral and angular positions around the fuel assembly (Figure 34).

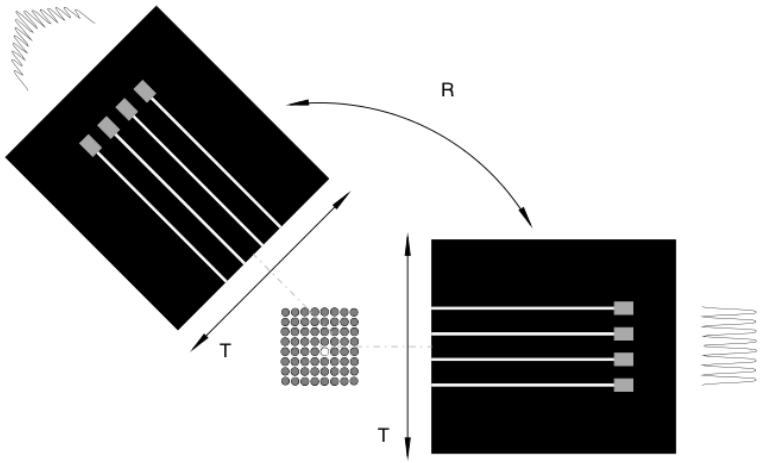

Figure 34: Schematic image of the translational (T) and rotational (R) movements involved in a tomographic measurement. The intensity pattern of radiation measured in one translation scan is indicated behind the detector/collimator package. Figure reproduced with permission from reference [53].

What is quantified: The 2D emission distribution at one axial level of the fuel assembly is quantified. The two main applications of the technique are

1. Integrity verification and
2. Determination of the pin-by-pin properties such as burnup and cooling time
3. Determination of pin-power distribution to validate production codes for core simulation at nuclear power plants.

Note that using tomography for measuring the ^{137}Cs distribution throughout the assembly should give a better correlation to decay heat than ordinary PG scanning (where only the outer pins are effectively seen by the detector).

Description of the basic physics: Tomographic reconstruction techniques are used to calculate the gamma-ray emission distribution using the measured intensity distribution.

Expected measurement time: Reference [54] estimated that 25 axial positions of a BWR assembly with ~1 month of CT could be measured in ~8 hours using 1596 keV of gamma radiation from ^{140}Ba. Note that the spent fuel of interested to Clink will be significantly older (10 to 70 years cooled) and that all the ^{140}Ba will have decayed away; for this reason, an isotope such as ^{137}Cs (662 keV) will be needed. A tomographic device to be used for partial or bias defect detection in 1-40 years cooled BWR, PWR or VVER 440 fuel have been designed in an IAEA coordinated research effort where the measurement time is in the order of one hour [55]. The area of a PWR assembly is about 1.5 × 1.5 times larger than a BWR assembly, which would imply a 2.25 times higher measurement time, due to the need for an increased number of measurement projections. It should be noted that the measurement time is inversely proportional to the number of detectors used in the

equipment. For instance, using the system described in Reference [54] but with 16 detectors, the measurement time per axial position would be ~10 minutes. Note that these measurement times are specified for the application to determine pin-power distribution, which needs better accuracy than the application to verify fuel integrity.

Work performed in Uppsala University shows that verification of fuel completeness is possible with the tomographic technique (see Figure 35) without prior knowledge of fuel type or geometry. Figure 35 shows an image produced by tomographic reconstruction techniques using no prior knowledge of the type of fuel assembly or other geometrical information. Using image analysis techniques, a histogram of rod positions was established whereby assumptions of "wrongly positioned fuel rods" could be detected as outliers in the histogram (red-coloured rods in Figure 35).

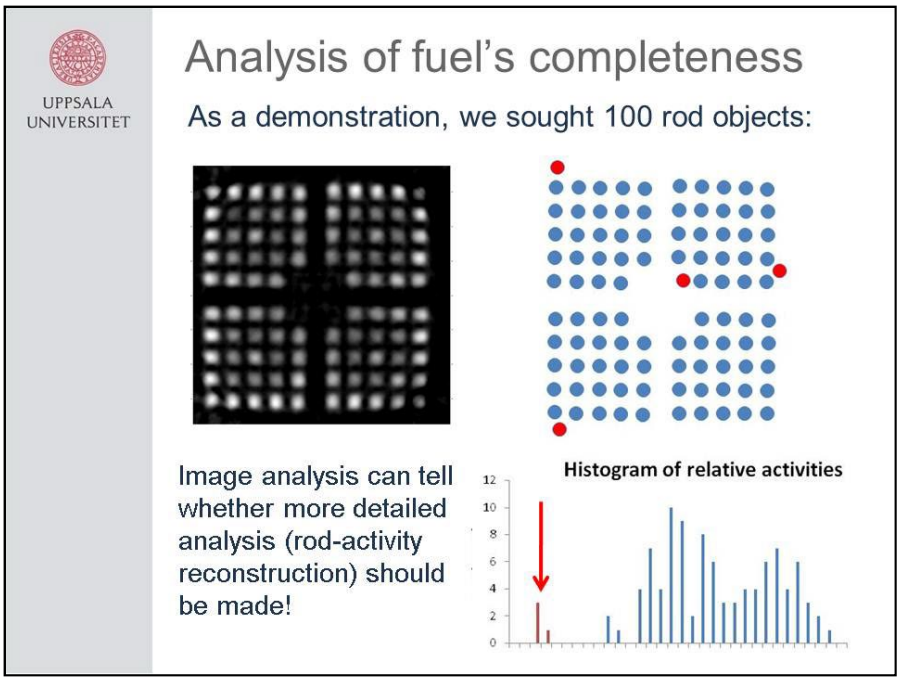

Figure 35: Using image analysis of tomographic measurements without prior knowledge of the fuel geometry or composition can provide enough information to determine both the geometry (which can be used for refined tomographic analysis) and verification of fuel completeness.

Safeguards inspectorates are now using the gamma emission tomography technique to verify the completeness and correctness of declarations of spent fuel assemblies and of spent fuel closed containers (for example, containers holding damaged pins) before they are transferred to dry storage. The instrument in use is called PGET (Passive gamma emission tomographer) [55] and it has been developed by the IAEA in close collaboration with international partners (among others, the EC, Finland, Germany and the US). It consists of two rotating batteries of 91 CZT sensors in a watertight enclosure, and it allows obtaining 2D reconstructions of almost any fuel geometry (PWR, BWR, VVER440 and most recently also VVER1000) with a few minutes' measurement. Figure 36 presents the principle of operation and a picture of a PGET.

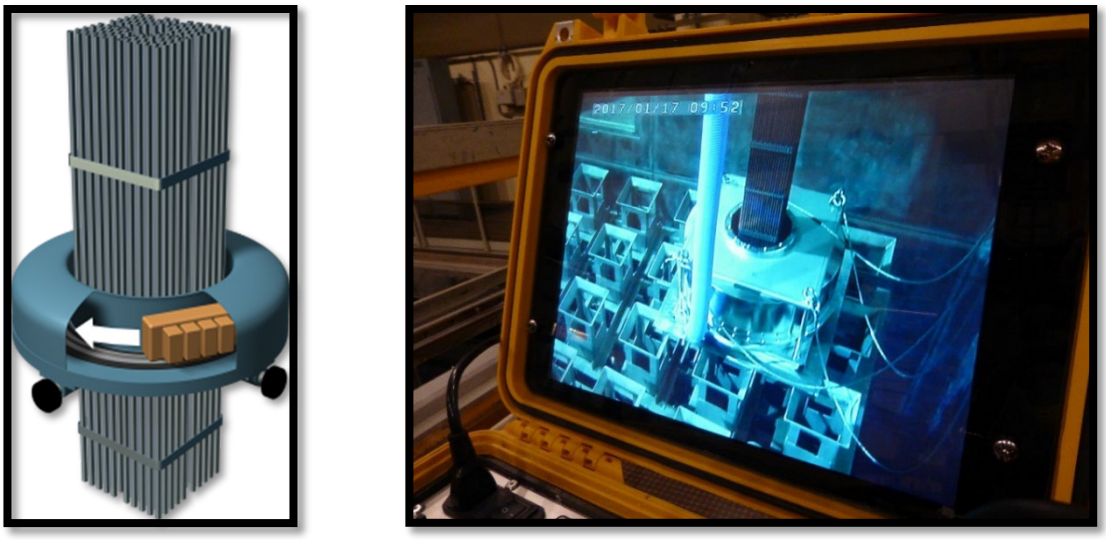

Figure 36: The principle of operation of the PGET is shown on the left picture. The right picture, taken with an underwater camera, shows an actual PGET measurement of a PWR spent fuel assembly.

5.9 Lead Slowing Down Spectrometer (LSDS)

What is measured: Prompt neutrons from induced fission as a function of incident neutron energy.

What is quantified: Conceptually the mass of ^{235}U, ^{239}Pu, and ^{241}Pu can be determined although the current analysis approach to such an absolute mass determination depend significantly on using fission chambers of each of these isotopes, only ^{235}U fission chambers are readily available. The relative mass of each of these isotopes is an easier goal than the absolute mass of any particular isotope.

Description of the basic physics: As illustrated in Figure 37, the spent fuel is positioned near the centre of a large cube of lead (~1.5 m on a side). An active neutron source sends out a burst (~10 μs in duration) of neutrons from near the centre of the lead cube [56]. These neutrons slow down gradually, given that they mostly collide with lead. During the time interval when the neutron energy is below the fertile fission cross sections, the prompt neutrons from the fission of ^{235}U, ^{239}Pu, and ^{241}Pu are measured. The unique features in the cross section of these three isotopes are used to unfold the amount of each isotope from the total measured prompt neutron signal. A key design goal is to keep the slowing down neutrons "tight" in energy, which is easy when the interrogating object is small but a challenge for a spent fuel assembly.

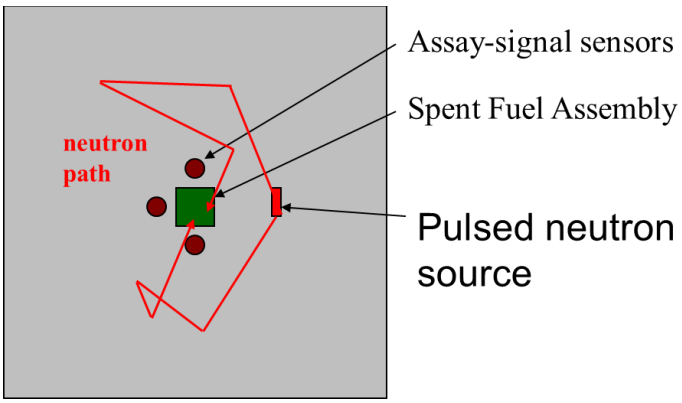

Figure 37: Conceptual design of an LSDS, indicating the location of detectors, fuel, and neutron source within the lead cube [56].

Of note, the presence of hydrogen in the cladding at levels of a several hundred parts per million makes a noticeable impact on the assay results. Another concern for LSDS assays is the penetrability of the neutrons into the assembly, particularly at lower neutron energies; the current analysis approach incorporates a self-shielding correction [56].

Expected measurement time: A rough estimation is that a 3×10^{12}-n/s neutron generator or accelerator is needed for ~1 hour to measure a ~1-m axial length of fuel.

5.10 Coincident Neutron (CN)

What is measured: Time-correlated neutrons from which doubles and triples count rates are calculated.

What is quantified: Multiplication or fissile content (weighted sum of ^{235}U, ^{239}Pu, and ^{241}Pu); for fissile content to be determined, a neutron absorber correction is necessary. Because the measured signal originates primarily from prompt induced fission for which nubar (average number of neutrons emitted per fission) and the fissile cross section are greater for fissile plutonium, the plutonium fissile isotopes are emphasised relative to ^{235}U.

Description of the basic physics: A conceptual design of a CN detector is depicted in Figure 38 and is identical to the conceptual DDSI detector. CN counting is a subset of multiplicity counting. For multiplicity counting using shift register logic, the number of counts in two different time windows is quantified. The first window is opened very soon after each detected neutron so that a neutron produced from the same initiating fission as the triggering neutron is more likely to be detected. The second gate is significantly separated in time from when the triggering neutron was detected such that any neutrons in the second gate are not correlated with the triggering event. A distribution is formed from the difference between the total counts in these two gates. From this distribution, the count rate for detecting coincident events, the doubles count rate, can be determined. The rate at which three correlated neutrons are detected or the triples count rate can also be quantified. The text "very soon after each detected neutron" is italicised above since this is the key statement that distinguishes the gates used by CN and DDSI.

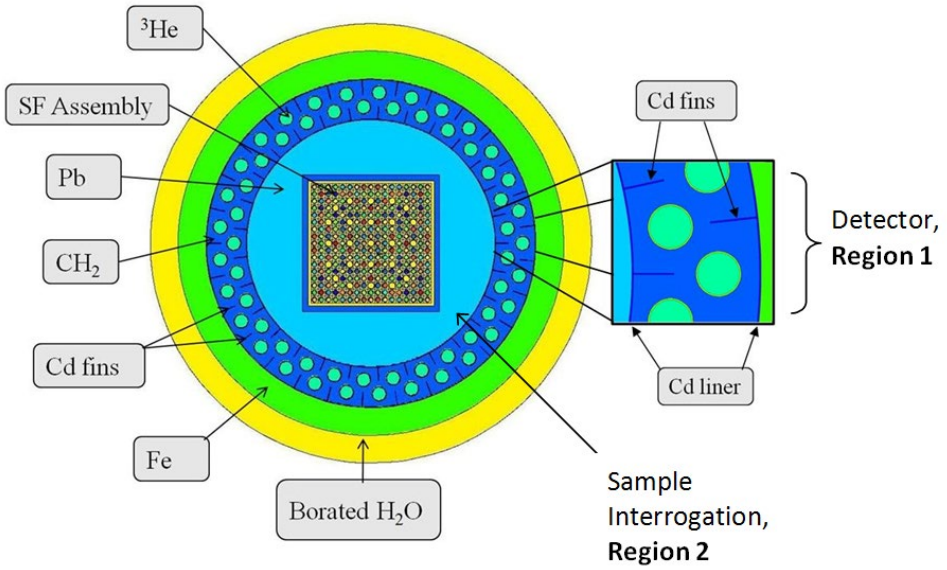

Figure 38: A design of a CN detector; Conceptual design of multiplicity instrument as simulated in MCNP for the NGSI Spent Fuel Project.

To perform shift register logic-correlated neutron detection, it is necessary to have a relatively efficient detector on the order of several percents at the very least. For such a system, the count rate in the context of spent fuel is so large that the accidental count rate for triples becomes very significant relative to true triples events such that the uncertainty on the triples count rate is excessive [57]. For this reason, only coincident counting, determination for the doubles count rate, is expected to be viable with spent fuel.

Expected measurement time: The measurement time for the doubles dictates the overall measurement time. For a 45 GWd/tU, 4 wt %, ^{235}U, 5-years-cooled assembly, a statistical uncertainty of 1% for the doubles can be obtained in roughly a minute for a 2 μs pre-delay and a 32 μs gate width.

5.11 Neutron Resonance Transmission Analysis (NRTA)

What is measured: The intensity of neutrons that have traversed the assembly as a function of energy. Because the intensity of neutrons incident on the assembly is known, the measured quantify is the percentage reduction in the neuron intensity as a function of energy.

What is quantified: The mass of four plutonium isotopes (238, 239, 240, and 242), four uranium isotopes (234, 235, 236, and 238), ^{241}Am, and several fission fragments [58].

Description of the basic physics: The NRTA assay starts with a burst from a pulsed high-energy particle accelerator, as illustrated in Figure 39. This burst of charged particles initiates a several-step process that results in the creation of neutrons with a range of energies; of particular interest to NRTA are the neutrons in the 0.1- to 40-eV energy range. The neutron burst is short enough in time and the neutron source is separated from the assembly far enough in space that a nearly uniform neutron energy arrives at the assembly at a given moment in time. These mono-energetic neutrons can scatter out of the beam as they interact with individual fuels pins in the assembly through low-energy elastic scattering, neutron-capture absorption, and neutron capture fission. The interaction of these quasi mono-energetic neutrons with the assembly can be measured by placing the neutron detector on the far side of the assembly from the neutron source. This setup provides the intensity of the transmitted beam as a function of neutron energy, which can be used to quantify how much of each isotope is in the assembly, provided the features of the spectra are detectable and do not interfere significantly with each other. Experimental results performed with spent fuel pins indicate that interferences are not significant.

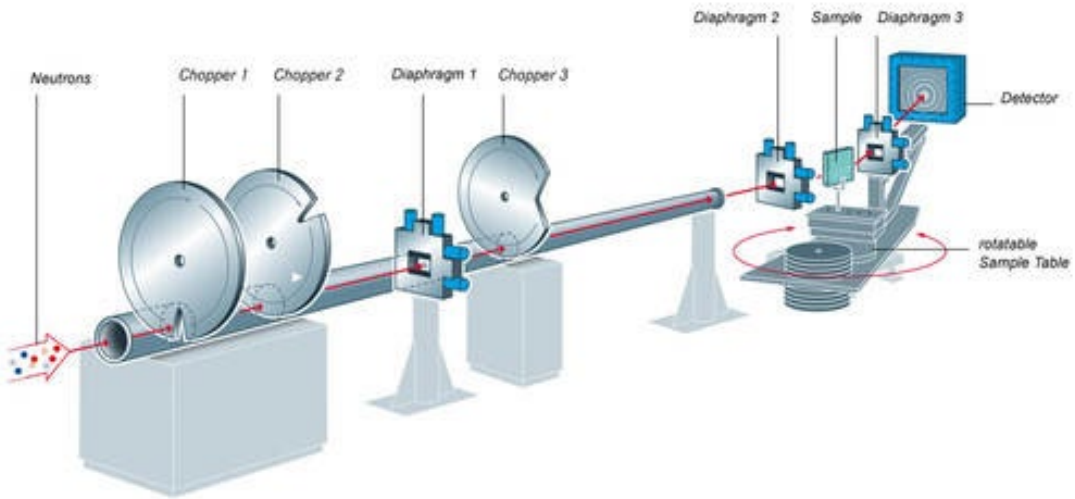

Figure 39: Schematic of a conceptual NRTA system.

Expected measurement time: The measurement time is expected to be ~40 minutes for an axial slice of one assembly when a ~1 × 10^{13}-n/s accelerator source is used to obtain a statistical uncertainty of ~5%. Note that several assemblies could be measured in parallel to use the neutron source more efficiently [58].

5.12 Nuclear Resonance Fluorescence (NRF)

What is measured: Given the thickness of a spent fuel assembly, the application of NRF to spent fuel studied by the NGSI Spent Fuel project focused on the NRF transmission measurement approach as opposed to backscattered NRF [59]. With transmission NRF, the absence of milli-electron-volt-level photons at a very specific energy are measured; note these resonances are significantly narrower than the energy resolution of typical detectors. The absence of photons at the resonance energy is indicative of the presence of the specific isotope.

What is quantified: The mass of any isotopes with a significant NRF cross section and sufficient mass to be detected; isotopes researched in the NGSI Spent Fuel Effort included ^{239}Pu, ^{240}Pu, and ^{235}U.

Description of the basic physics: As illustrated in Figure 40 NRF is a two-stage process that involves the excitation of a nucleus by the absorption of a photon, which is then followed by the de-excitation of the nucleus to the ground state by the emission of one or more photons. In the transmission approach to NRF researched for spent fuel assembly assay, a relatively flat photon spectrum is incident on the assembly from a bremsstrahlung source. If a particular isotope of interest is present in the fuel, it will absorb photons at the resonant energy from the incident beam, then will re-radiate photons into all space. As a result, the photon intensity in the incident (nearly flat spectrum) beam will be depressed at the resonant energy of the isotope of interest. Thus, as the incident continuum traverses the assembly, the presence of a specific isotope is indicated by a depression in the continuum—the greater the amount of an isotope present, the greater the depression in the spectrum.

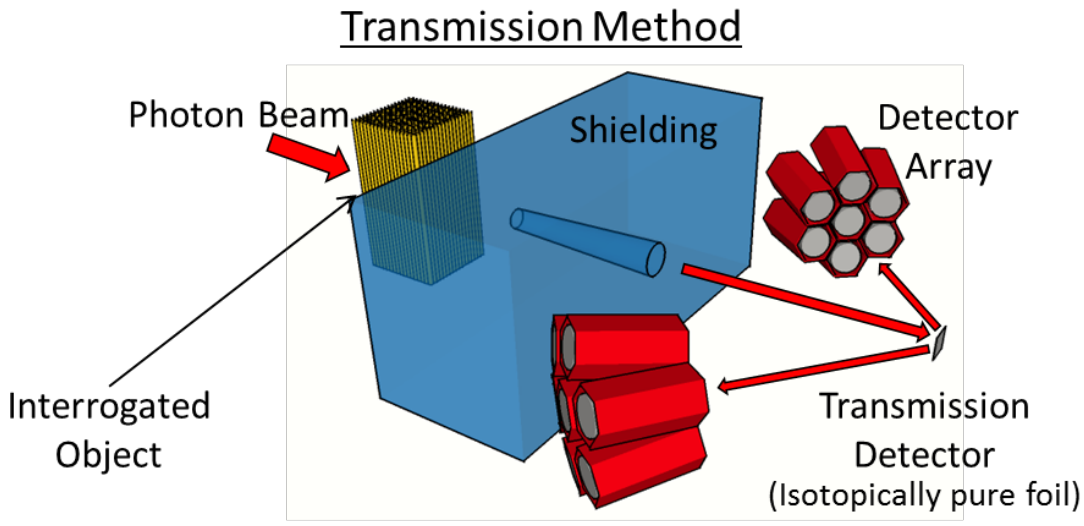

Figure 40: Conceptual design of an NRF measurement of spent fuel using the transmission method [59].

Expected measurement time: Because it is an active interrogation technique, the measurement time depends on the intensity of the interrogating source. Practically speaking, a very strong source is needed to obtain reasonable statistics in <1 hour.

5.13 Passive Gamma (PG)

What is measured: The axial profile of the intensity of gamma radiation for ~0.5 MeV to ~2.5 MeV in energy (see Figure 41).

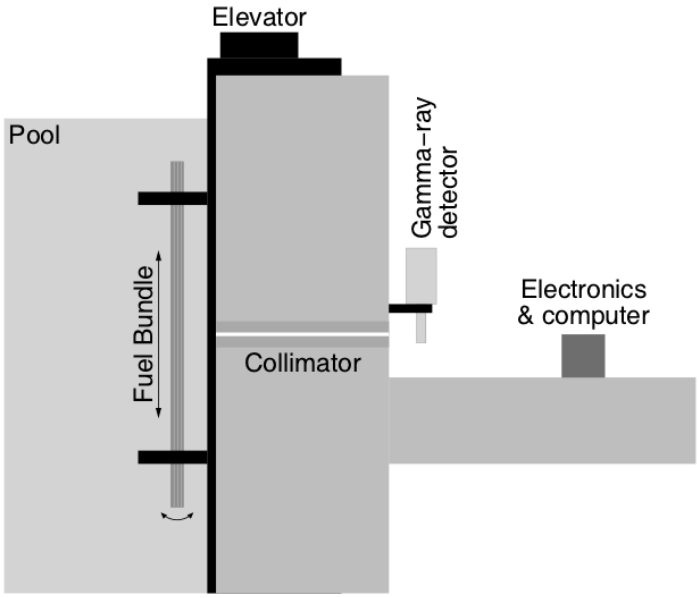

Figure 41: A schematic image of a PG scanning system in use at the Clab Facility, Oskarshamn, Sweden. Figure reproduced with permission from reference [53].

What is quantified: Isotope specific gamma radiation from ^{134}Cs, ^{137}Cs and ^{154}Eu can be used to determine the fuel parameters BU, IE, and CT for spent fuel with a CT less than ~20 years. Beyond that time, ^{134}Cs has decayed significantly, and IE and CT have to be determined by other means. The longer half-life (~30 years) of ^{137}Cs implies that it can be used to determine BU for a longer time [60]. Decay heat can also be inferred from gamma scanning data using a calorimetric calibration (see Section 1.2). Reference [61] complements the applicability of PG scanning with the ability to indicate the following:

- Determine the concentrations of fission products and their distribution within the assembly and thus the comparison between calculated and experimentally determined power distribution parameters.
- Use the fission product distribution for accurately locating the fuel stack within the fuel rods and for determining dimensional changes in the fuel, e.g., axial fuel swelling and gaps in the fuel pellet stack within the fuel rods (relevant for gamma scanning of single fuel rods).

Expected measurement time: A complete gamma scan of a fuel assembly takes on the order of 15 minutes, which includes spectra-resolved information on the gamma intensity reaching the detector.

5.14 Passive Neutron Albedo Reactivity with Fission Chambers (PNAR-FC)

What is measured: TN count rate for two different physical setups, one setup designed to maximise multiplication and the other designed to minimise multiplication.

What is quantified: Multiplication or fissile content (the weighted sum of ^{235}U, ^{239}Pu, and ^{241}Pu); for fissile content to be determined, a neutron absorber correction is necessary. Because prompt fission-based multiplication is measured, PNAR-FC emphasises the presence of ^{239}Pu and ^{241}Pu per unit mass. For thermally

induced prompt fission per unit mass, ^{239}Pu and ^{241}Pu produce ~1.5 and ~2.0 times as many neutrons as ^{235}U, respectively.

Description of the basic physics: PNAR-FC, the conceptual hardware illustrated in Figure 42 uses the intrinsic neutron emission of the fuel to self-interrogate the fissile material in the fuel itself. Two separate measurements of the spent fuel are made. The primary difference between the two measurements is the neutron energy spectrum and fluence in the spent fuel—this difference was primarily achieved by surrounding the fuel with cadmium for one of the two measurements [62], [63]. By varying the material around the spent fuel, a high and a low neutron-energy-measurement condition can be produced (low and high multiplying setups, respectively). The ratios of the count rates obtained for these two situations correlate with the multiplication and fissile content in the spent fuel case. The primary difference between the two PNAR-FC measurements from an energy spectrum perspective is the presence of reflected neutrons with an energy below the cadmium cut-off energy (~0.5 eV); the PNAR-FC instrument can be considered to be an interrogation technique for which the interrogating source is essentially thermal neutrons incident from all sides of the assembly.

Expected measurement time: The count rate for a fully burned 45-GWd/tU, 4 wt %, ^{235}U, 5-years-cooled assembly is ~1 × 10^5 counts/s; for a similar assembly after one cycle, the count rate is roughly 100 times lower [63]. Thus, counting statistics are excellent in ~100 s.

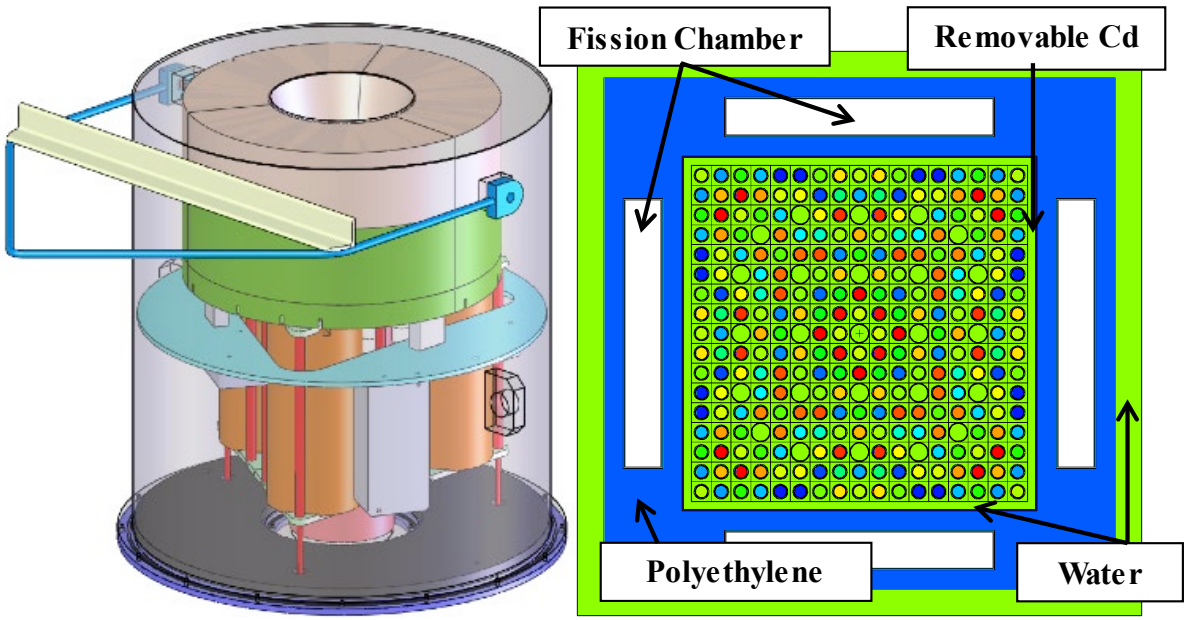

Figure 42: Top: Mechanical design of a PNAR instrument for measuring circular fuel. Down: Conceptual design of a DG instrument as simulated in MCNP for the NGSI Spent Fuel Project [63].

5.15 Self-Integration Neutron Resonance Densitometry (SINRD)

What is measured: The neutron intensity in four different parts of the TN spectrum. If the material in the fission chamber matches that of the isotope of interest, then the sensitivity to the presence of the material of interest is enhanced because of the resonance energy structure [64], [65]. For example, a ^{239}Pu fission chamber is more sensitive to the presence or absence of ^{239}Pu than a ^{235}U fission chamber although both will

work for SINRD given the use of absorptive filters. The utility of matching the isotope of interest to the material in the fission chamber is due to the fact that a ^{239}Pu fission chamber is particularly sensitive to the presence or absence of neutrons at 0.3 eV because this is a resonance of ^{239}Pu; if there is a significant amount of ^{239}Pu in the fuel, then there will be relatively few neutrons leaving the fuel with an energy of 0.3 eV.

What is quantified: The mass of ^{239}Pu for medium and full BU fuel; for low BU fuel when a large amount of ^{235}U is present, a correction is needed [65].

Description of the basic physics: In the right-hand side of Figure 43 the locations of the various fission chambers in the SINRD unit are depicted. In the left-hand side of Figure 43, a SINRD unit built for deployment is illustrated. In Figure 44, the neutron energy spectrum for five 4% IE assemblies is illustrated as a function of energy, one fresh assembly, and four spent assemblies, each with a different BU.

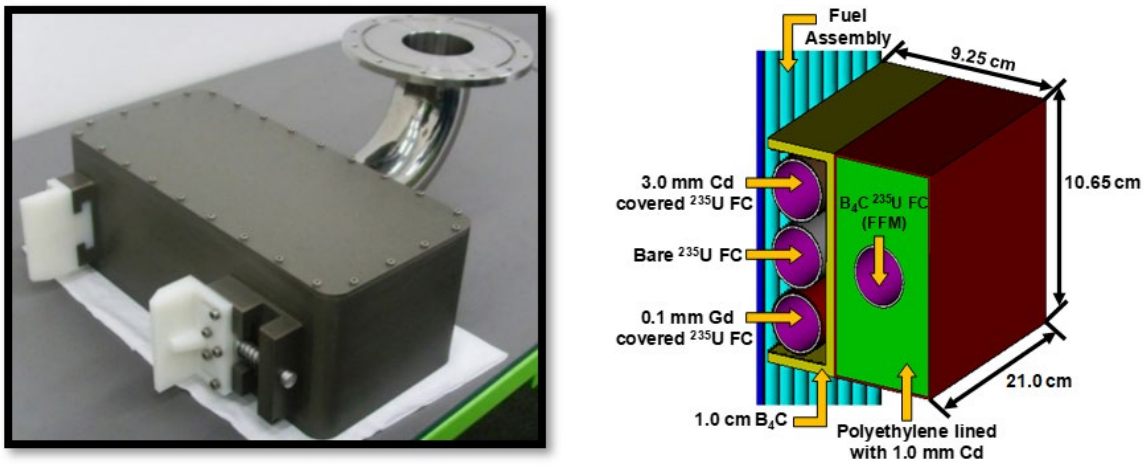

Figure 43: Left: Fabricated SINRD prototype for spent fuel measurement. Right: Conceptual design of SINRD instrument as simulated in MCNP for the NGSI Spent Fuel Project [65].

The fundamental physics of SINRD is captured in Figure 44, which depicts the flux averaged over all the pins in the assembly such that the area under the curve is proportional to the flux. The largest "peak" at ~2 MeV is the "fast" birth energy of most neutrons following fission. These fast neutrons moderate by colliding in the water and fuel. The second major peak is at thermal energy and is formed by the neutrons that manage to "survive" all the collisions they underwent in the thermalisation process and still reside in the fuel. The structure in the spectrum is the result of particularly prominent absorption processed; of particular note are a few of the resonance absorption due to ^{238}U, ^{240}Pu and ^{239}Pu, which are illustrated in Figure 44. The SINRD detector comprises four fission chambers. By surrounding the fission chambers by absorbing material (cadmium, gadolinium, hafnium, and boron) of specific thicknesses, each fission chamber detects a different part of this spectrum. By calculating the difference and ratio among the count rates in these fission chambers, the SINRD signal is determined. This signal is proportional to the ^{239}Pu and ^{235}U content in the fuel.

Expected measurement time: The count time for SINRD is largely determined by the ambient neutron emission of the fuel, the intensity of which varies roughly as the third or fourth power of the BU. For fully burned assemblies, this emission can result in count times of between 5 and 20 minutes for a ~20-cm axial length along one side of the assembly. For one cycle of fuel, it may take 2 hours. Note: An active neutron source can be used to reduce the count time.

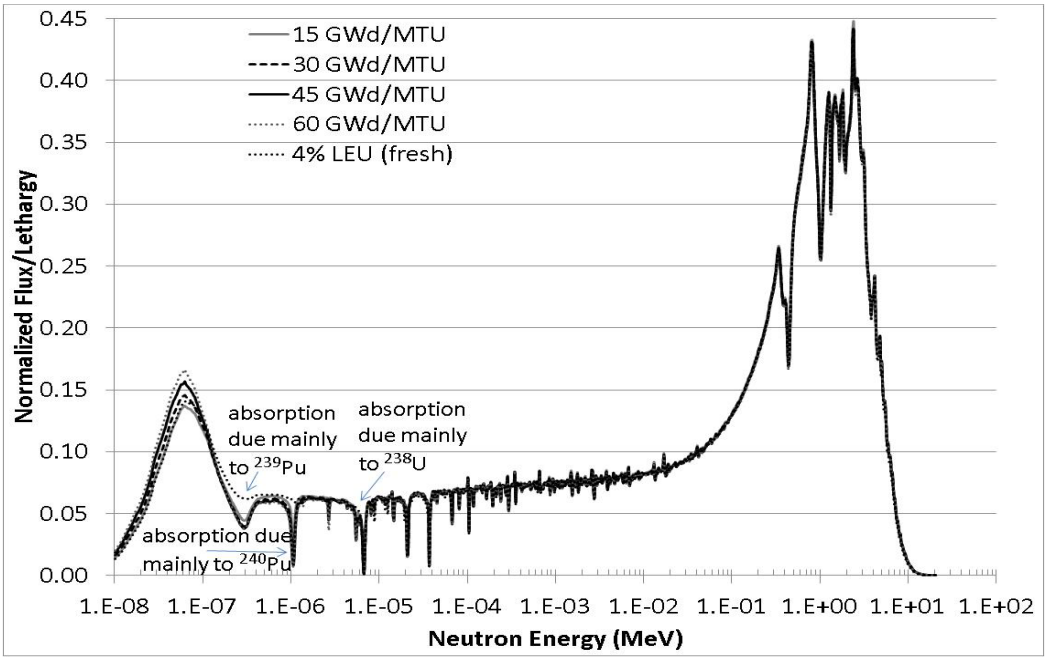

Figure 44: Normalised neutron energy spectrum in the fuel rods for five different fuel assemblies [65].

5.16 Total Neutron (TN)

What is measured: TN emission, also known as singles counting.

What is quantified: Provides information about coupled parameters of IE, BU, and CT; the three parameters can be determined in combination with PG. The signal is proportional to the product of the multiplication and the passive neutron source, which is dominated by ^{244}Cm for most spent fuel assemblies. The TN rate can also be a rough indicator that the assembly is whole.

Description of the basic physics: Radioactive material in spent fuel emits neutrons. The dominant spontaneous fission isotopes are generally ^{244}Cm, ^{242}Cm (for short CT), and ^{240}Pu. The (α,n) sources also contribute, particularly for low BU or long CT.

Expected measurement time: Less than 1% counting statistics uncertainty is obtained in less than 10s.

5.17 X-Ray Fluorescence (XRF)

What is measured: Uranium and plutonium x-rays from a volume that is a few mm square in surface area and ~1 mm deep into the fuel from an individual exterior rod. It is likely that multiple detectors would be used to measure various locations on a rod or side of an assembly.

What is quantified: The elemental plutonium mass of the assembly.

Description of the basic physics: Plutonium to uranium X-rays are stimulated by the radiation emanating from the spent fuel: both photon and charged-particle excitation. A conceptual design of an experimental setup for XRF detection from spent fuel is depicted in Figure 45. The elemental ratio of plutonium to uranium in the edge layer of the spent fuel can be determined by measuring these x-rays and taking the ratios of their intensity. A correction needs to be made to account for the radial profile of these isotopes particularly in the case of plutonium which ramps up by a factor of 2 to 3 in the outermost ~0.2 mm. Once this correction is made the average elemental plutonium-to-uranium ratio can be estimated [66]. The absolute plutonium is estimated by multiplying the average elemental plutonium-to-uranium ratio by the total amount of uranium in the rod. The mass of elemental uranium can be well estimated in a spent fuel rod. When an assembly is

fresh, ~88% of the mass is elemental uranium; at the end of life, elemental uranium is ~82% of the total mass in the rod. The change between these two extremes can be accurately estimated from gamma or neutron measurements such that the uncertainty in the amount of uranium can be estimated to less than 1%. The final step involves extrapolating from the measured plutonium mass in the edge rods all around the exterior of the assembly to the entire assembly. This step is done through simulation, and preliminary results within the NGSI-SF Project (2) indicate that the uncertainty in this process is likely a few percent. The general conclusion from the preliminary research is that if the boundary plutonium mass is known, the centre plutonium mass can be predicted accurately. In all this discussion, it must be emphasised that because the mean free path of the ~100-keV x-ray photons is ~0.5 mm in fuel, the extrapolation assumes that no diversion of rods from the assembly exists. XRF is completely blind to the diversion of pins from anywhere but the exterior rods of an assembly.

Expected measurement time: Approximately a 10 hours measurement time was estimated from simulation for a ~3% uncertainty in plutonium x-ray intensity for an assembly when a single planar detector was used. During measurements of individual rods ~2% uncertainty was obtained in ~2 hours. The difference between these two examples is not well understood.

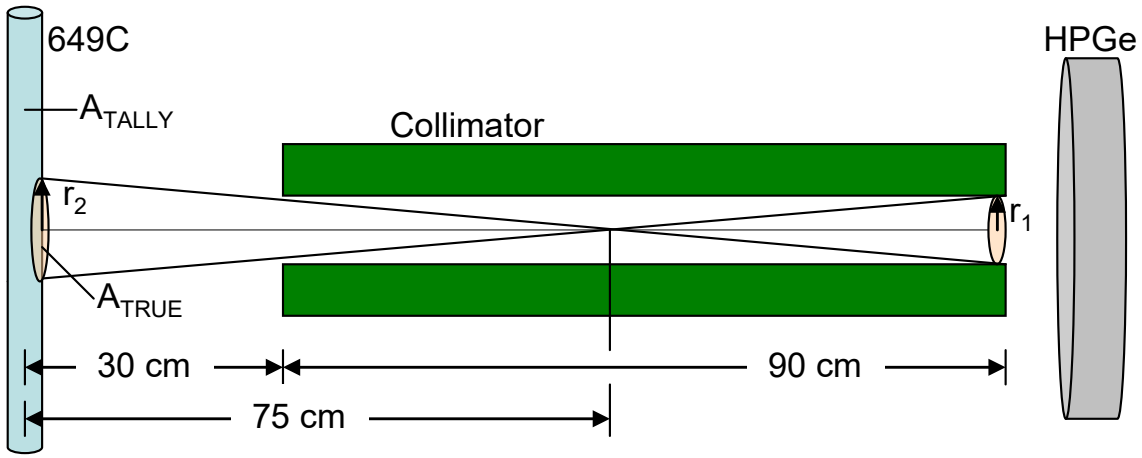

Figure 45: Conceptual design of an XRF setup.

5.18 Fork Detector

What is measured: The gross neutron and gamma intensity using the Fork Detector Irradiated Fuel Measuring System (FDET) (see Figure 46), [67] and [68]). An enhanced version of FDET has a CdZnTe detector, which provides spectrally resolved gamma data primarily from the sub-MeV energy range.

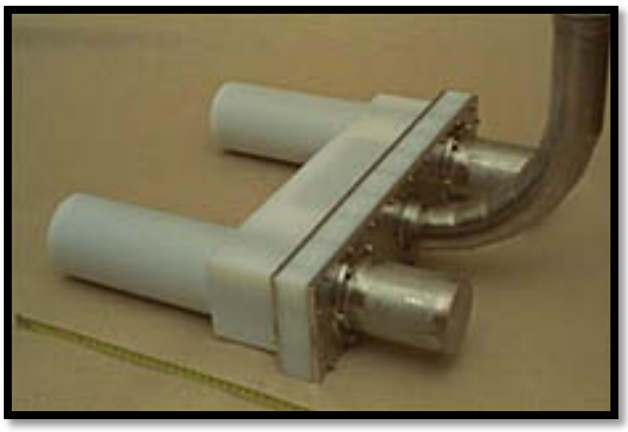

Figure 46: An FDET.

What is quantified: The TN and total gamma counts are used for the gross defect detection and verification of declared data. The ratio between neutron and gamma-ray counts can be used to characterise a fuel assembly (i.e., the in-core neutron exposure, the initial fissile content, and its irradiation history). The measured neutron count rate is related to the BU and CT of the spent fuel.

Description of the basic physics: The neutron detectors are gas-filled fission chambers, and the gamma detectors for the traditional Fork detector are gas-filled ionisation chambers. The signal from these detectors is proportional to the gross (i.e., total measured signal without background subtracted) neutron and gamma intensity; the enhanced Fork detector has energy-resolved spectral information.

Expected measurement time: Measurements that were performed at the Clab Facility in 1997 lasted 2 minutes and resulted in better than 1% statistical uncertainty.

5.19 Partial Defect Tester (PDET)

What is measured: Total neutron (fission chambers) and total gamma (ion chamber) count rates measured by small detectors that move down guide tubes within an assembly (the hardware and a sample of the data are depicted in Figure 48 [69]. This measured signal can practically be obtained only if guide tubes exist for the detectors to go down, which eliminates some assemblies (most notably BWR assemblies) from measurement.

What is quantified: Primarily detecting if pins are missing by detecting a localised variation in the neutron-to-photon ratio in the assembly. Information regarding BU and CT is also obtained. It is expected that diversion of ~10% of the mass can be detected [69].

Description of the basic physics: This integrated system combines PG and TN, as do the Fork and the SMOPY integrated systems. What makes PDET unique is the spatial information that is obtained by putting the detectors down the multiple guide tubes of a PWR assembly. In the right-hand side of Figure 48, both simulated and measured PDET data are illustrated. The "normalised ratio" is the normalised ratio of the gamma-to-neutron count rates. Each point on the "Detector" axis represents a different guide tube location. The green "J14" curve is the expected signal for the assembly if no pins were missing. In the case of the J14 assembly that was measured at the Korean Atomic Energy Research Institute (KAERI), some pins were not present [69]. The "Sim" and Meas" curves in Figure 47 are the simulated and measured results with 22 pins (12% of the mass) missing, respectively. The difference between the "J14" and "Sim" and Meas" quantifies the change in the ratio when a diversion has occurred.

Expected measurement time: The time needed to measure one assembly will likely be dominated by the time it takes to attach/align the detector structure to the assembly. It is expected that the actual measurement of neutron and photon will take less than 5 minutes for most assemblies.

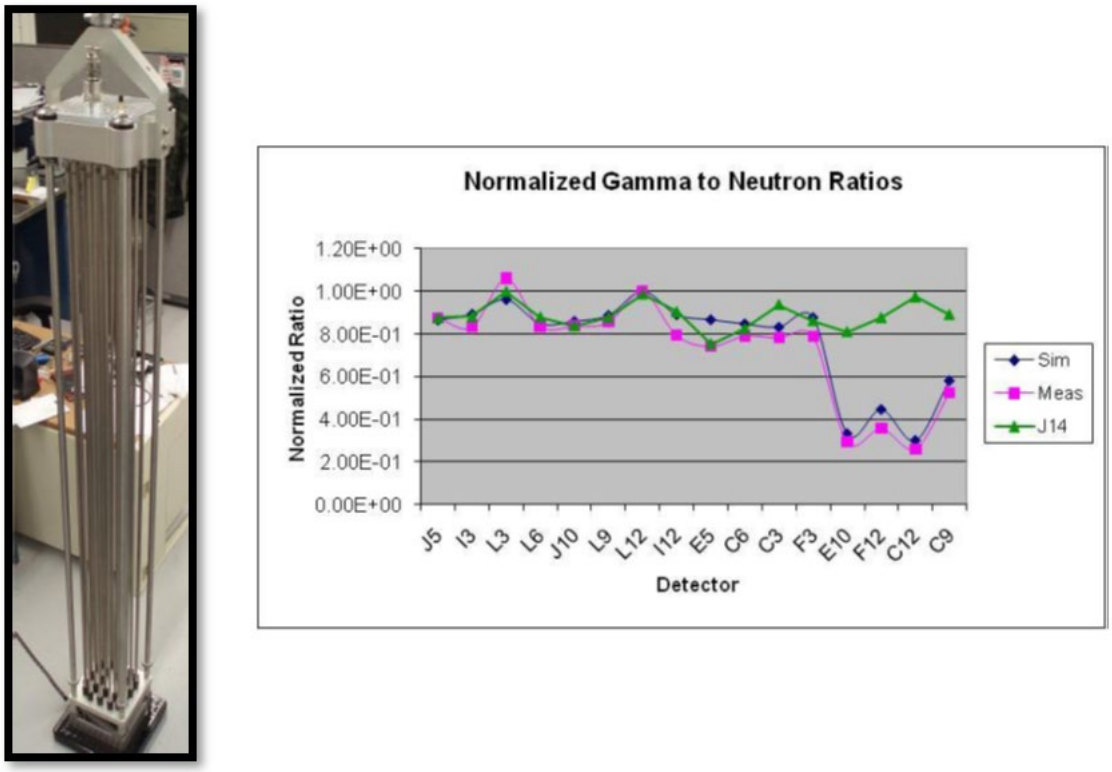

Figure 47: Left, [69]: Photograph of a prototype PDET system. Right: Simulated and measured PDET data. The "normalised ratio" is the normalised gamma-to-neutron count rate. Each point on the "Detector" axis represents a different guide tube location. The "Sim" and Meas" curves are the measured and simulated results for a particular assembly that had missing pins. The "J14" curve is the expected signal for the assembly if no pins were missing.

5.20 Safeguards Mixed Oxide (MOX) Python (SMOPY) Detector

What is measured: Gross neutron intensity and spectra resolved gamma intensity. The gamma intensity is measured with relatively poor energy resolution, but the peaks of interest are resolved.

What is quantified: A shielded CdZnTe gamma spectrometer and a fission chamber are used to distinguish MOX fuel from LEU fuel and to verify the BU and CT [70]. A partial defect test of the used fuel can be performed using operator-declared data for depletion calculations (see Figure 48).

Figure 48: A SMOPY detector. Description of the basic physics: Passive neutron and gamma spectrometry is combined (see the physics description for PG scanning and passive neutron measurements).

5.21 Summary of NDA Techniques

The following characteristics of most of the NDA techniques described here are summarised in 12: (1) the impact of changing the fuel type from PWR to BWR assemblies, (2) the maturity of the hardware and the impact of this hardware in the facility, (3) the degree to which the signal is proportional to mass located at various depths inside the assembly, and (4) the count time per unit length.

The simulation results on which much of the evaluations of the techniques are based, were performed on PWR assemblies. An important question is how the various NDA techniques perform for BWR assemblies. In transitioning from PWR to BWR assemblies, the following changes are of note for most NDA techniques: (1) There is a greater axial variation in all isotopes along the assembly (fission products as well as fissile isotopes); (2) the IE and pin geometry can vary within one assembly (axial and radial variation); and (3) the cross-sectional area of the BWR (8 × 8, 9 × 9, and 10 × 10) assemblies is less than the 17 ×17 PWR assemblies; (4) a zircaloy sheet surrounds the bundle for PWRs; and (5) the absorber blades, which can be thought of as a zircaloy cross, will be inserted into some assemblies.

The first two points in the previous paragraph increase the uncertainty in making the connection between a measured signal and a particular quantity, such as plutonium mass, fissile content, or diversion detection. The increase in the isotopic spatial variation impacts both the BU calculations and the interpretation of measured data. The BU calculations are expected to be less accurate for BWRs; thus, any analysis that uses the BU calculation is less accurate. The interpretation of the measured values is more uncertain because it is more important to know accurately the origin of the signal. The signals that propagate through multiplication in the assembly are not expected to be very sensitive to the BWR-introduced spatial variation. Effectively, multiplication averages over the isotopic variation within the detector.

The inclusion of additional zircaloy in BWRs is not expected to be of significant concern for neutron techniques in terms of perturbing the actual measurements; the neutrons will easily penetrate through the zircaloy just as they did in the reactor. The presence of neutron absorber in the zircaloy is not expected to be a significant problem provided the absorber concentration evolved in a consistent way with the fuel BU. For photon techniques the zircaloy will not impact high energy photons, above ~0.5 MeV, much and the attenuation that is experience can be corrected for. However, low energy photons, particularly in the X-rays and the 60-keV peak from ^{241}Am may experience very significant attenuation.

The presence of burnable poisons in the fuel is not, in and of themselves, a problem. All the neutron techniques "work" with the absorbers that burn into the fuel (^{240}Pu, ^{143}Nd, ^{155}Gd, ^{149}Sm, ^{241}Am, etc.). Because the concentration of burnable poisons is of the order of magnitude as these "natural thermal absorbers," the neutron NDA techniques are expected to give strong signals.

The hardware of an instrument was considered to have a "high maturity" if all parts are currently commercially available. The impact of an instrument was considered "low" if it could be retrofitted into a facility with little or no effort. The penetration was considered "good" if the signal had roughly the same sensitive to pins removed from any region of the assembly.

Table 12: Summary of the (1) Relative Impact of Changing the Fuel Type from PWR to BWR Assemblies, (2) Maturity of the table Hardware and the Impact of This Hardware in the Facility, (3) Degree to Which the Signal Is Proportional to Mass Located at Various Depths inside the Assembly, and (4) Count Time per Unit Length.

Techniques	Uncertainty introduced in due to transitioning from PWR to BWR (no, some, med., med.-high)	Maturity of Hardware (H) Analysis (A) and Impact (I) on Facility	Penetration of Signal inside Assembly	Measurement Time per Axial Unit Length and General Comments
CIPN	Some	High H, Med-Low A, Low I	Good	<100 s per 20 cm
CDH	No impact	High H, High A, Med. I	Excellent	4-5 hours per assembly
DG	Medium	Med. H, Med.-Low A, Med. I	Signal weighted to exterior	~30 minutes per ~50 cm, system outside pool likely ~2-m^2 footprint
DN	Some	Med. H, Med. A, Med. I	Good	~100 s per ~50 cm, system outside pool likely ~1-m^2 footprint
DDA	Some	High H, Med. A, Med. I	Good	~100 s per ~50 cm
DDSI	Some	Med. H, Med.-Low A, Med. I	Very Good	~15 minutes per ~50 cm
DCVD	No significant impact	High H, Med. A, Low I	Poor	<100 s for entire assembly
Passive GT	BWR easier than PWR	Med.-Low H, Med. A, High I	Excellent	About 10 minutes per axial position
LSDS	Some	Med.-Low H, Med.-Low A, Med.-High I	Good	Must measure in air, moderately large footprint
CN	Some	Med. H, Med.-Low A, Med. I	Good	~5 minutes per ~50 cm
NRTA	BWR easier than PWR	Med.-Low H, Med.-Low A, High I	Signal weighted to exterior	Must measure in air, large footprint[a]
NRF	BWR easier than PWR	Low H, Med.-Low A, High I	Conceptually Excellent	Not considered a viable option with currently available technology[b]
PG (total and spectral)	Medium-High, the metal box of a BWR may reduce signal somewhat	High H, High A, Low I	Signal from outer 2 or 3 rows	Total gamma, ~10 s per ~20 cm; spectral resolved gamma, ~10 s for ~1 cm axial length[c]
PNAR-FC	Some	High H, Med. A, Low I	Good	~100 s per ~50 cm
SINRD	Medium-High	High H, Med.-Low A, Low I	Signal from outer 2 or 3 rows	<15 minutes for 20 cm for most spent fuel[d]
TN	Some	High H, High A, Low I	Good	~10 s per ~20 cm
XRF	Medium-High for PWR, the metal box of a BWR may significantly reduce signal	Medium H, Med.-Low A, Medium I	Signal from outer few mm of exterior pins	Moderately large footprint, count time largely dependent on number of detectors.

[a]Could measure multiple assemblies in parallel, several hours per meter for one assembly.

[b]Sensitivity is very low with a Bremsstrahlung source and thus not considered a viable option until mono-energetic photon sources of sufficient technology are available.

[c]Many variables can impact this parameter: number of detectors, attenuator thickness, and collimation. Note: If desirable, the detection of the 60-keV gamma from ^{241}Am would need a separately designed collimator and no significant attenuation.

dCount time can be more than 1 hour for one cycle fuel.

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Destructive Sample Analysis for Nuclear Safeguards

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Abstract

Samples taken by safeguards inspectors for verification purposes can be analysed using various measurement techniques. These are selected according to sample type and analytical or safeguards requirements. This paper will focus on destructive analysis, describing the most commonly used techniques and stressing the importance of quality control tools for confidence in measurement results. Some examples are given of the use of reference materials and of the capabilities of laboratories performing verification measurements.

1 Introduction

By signing the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), non-nuclear weapon states officially declare to abandon all efforts to develop nuclear weapons and commit to conclude comprehensive safeguards agreements enabling the verification of treaty compliance [1]. This verification task is performed by safeguards inspectorates. Safeguards agreements exist on international level under the protocols of the International Atomic Energy Agency (IAEA) and on European Union level under the Euratom Treaty [2]. Initially, safeguards measures focused on the verification of declared activities and declared amounts of material. In this regard, the technical objective is specified: "the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection" (INFCIRC/153 corrected [3]). This is verified through independent measurements, hence providing assurance that nuclear material is not diverted (without being detected) from its declared peaceful use.

In 1991 inspectors detected evidence of a clandestine uranium enrichment programme in Iraq, involving undeclared nuclear material and undeclared activities. This led to the implementation of strengthened safeguards systems and the publication of INFCIRC/540 [4], also referred to as the Additional Protocol (AP). The aim was to move from an exclusively quantitative system focused on verification of declared amounts of nuclear material towards a more comprehensive picture of a state's nuclear activities for verifying the absence of undeclared nuclear materials and activities.

Safeguards are a set of technical measures applied to nuclear materials and activities, through which we seek to independently verify that nuclear facilities are not misused and nuclear material is not diverted from peaceful uses. These consist of a combination of determination of mass and/or volume and the analysis of samples taken from the bulk. In safeguards terminology, measurement techniques are characterized as being "non-destructive" (i.e. without producing significant physical or chemical changes in the item) or as "destructive" (i.e. involving destruction of the physical form of the sample). In other words, "non-destructive" techniques typically measure entire items (without taking samples) while "destructive" techniques require sample taking, hence affecting the integrity of an item. The nuclear material sampling procedure should

guarantee that the sample is indeed representative of the bulk. Furthermore, it has to be ensured that the sample is not tampered with on its way from the sampling station to the measurement laboratory [5].

The system of measurements applied in nuclear safeguards is requested to comply with the latest standards or being equivalent in quality to such standards. Analytical methods and measurement techniques in combination with the correct use of reference materials and quality control tools provide reliable measurement results for the independent verification of nuclear material and environmental samples [6].

The present chapter addresses the "destructive" techniques and will describe both sets of analytical methods; the so-called “bulk sample analysis” for verification of declared amounts of material and the “environmental sample analysis”, for detection of undeclared nuclear activities.

2 Sample Types in the Facilities

Depending on the nature of the nuclear facility, different types of samples are handled. This includes different chemical compositions, physical appearance and handling techniques. The key elements of the nuclear fuel cycle immediately determine the types of samples to be expected [7].

2.1 Mining/Milling

Nuclear material safeguards start when "any nuclear material of a composition and purity suitable for fuel fabrication or for being isotopically enriched" leaves a facility or a process or enters a State. In consequence, there is no strictly defined starting point of safeguards. However, with the Additional Protocol and with the implementation of Integrated Safeguards, also samples of uranium ore concentrate - if of sufficiently high purity - are subject to safeguards. Uranium ore concentrates are provided in a variety of chemical compositions such as uranium peroxide, ammonium di-uranate, sodium di-uranate, ammonium uranyl carbonate or uranium tri-oxide. Measurement of chemical impurities and of the isotopic composition might be requested on such samples.

2.2 Enrichment

Uranium hexafluoride (UF_6) is the material exclusively handled in commercial enrichment facilities operated for the production of low enriched uranium (LEU) for the production of reactor fuel. Because of its chemical properties, UF_6 has to be handled in closed confinements under dry atmosphere. At ambient temperature UF_6 forms a solid. Its high volatility favours the application of thermal transfer processes (i.e. sublimation and distillation), which serve at the same time to homogenize the material. The ^{235}U enrichment as well as the uranium content are parameters that have to be measured, frequently the minor abundant uranium isotopes ^{234}U and ^{236}U are also measured. Recently, also the chemical impurities are determined in order to check consistency of material characteristics with declared processes.

2.3 Fuel Fabrication

There are two major categories of fuel in the civil nuclear fuel cycle: uranium oxide and U/Pu mixed oxide fuel (MOX) [7]. After conversion of the UF_6 to UO_2 the material is first handled in the form of a powder. After pressing and sintering, pellets are used for the actual fuel pin fabrication. Hence, samples of UO_2 powder and pellets have to be analysed for ^{235}U abundance and uranium content. The fine powders, due to their high surface area, tend to pick up moisture from the air and consequently show changes in weight. This affects the analysis results, as the uranium content appears to decrease with increasing moisture pick up. Careful recording of the sample mass is therefore required in order to correct for this effect (so called weight change correction).

MOX fuel is manufactured from uranium and plutonium base materials. Depending on the production process, U and Pu solutions or UO_2 and PuO_2 powders are used as starting materials. These however, are usually not measured (for safeguards purposes) in the fuel fabrication facility as this is already done at the reprocessing facility. In contrast to that, the products, i.e. the MOX pellets, are intensively verified. These samples have to be analysed for uranium and plutonium content as well as for their isotopic composition.

In the future new reactor designs, the so-called Generation IV reactor types (Gen IV), are expected to use metallic fuels or fuels of high initial ^{235}U enrichment. The primary goals of Gen IV reactors are to be more economic, to improve nuclear safety and proliferation resistance while minimizing waste [7, 8]. Up to now these kinds of fuels are not commonly used in commercial reactors for electricity generation. They represent therefore only a marginal fraction of the whole fuel production but are nevertheless of high relevance to Safeguards Authorities. Samples of these types of fuel are part of the future challenge for the system of measurements applied in nuclear safeguards.

2.4 Reprocessing

Irradiated nuclear fuel can be reprocessed after an appropriate cooling time. Most of the reprocessing processes are based on liquid-liquid extraction for the separation of the valuable materials, uranium and plutonium [7]. Research into pyro-processing of spent fuel is ongoing as part of advanced reactor systems, but to date the most widely used technique is the so called PUREX process [9, 10]. The first step, therefore, is to dissolve the fuel. The solution (reprocessing input solution) is stored in the input accountancy tank. Samples of the solution are taken from this tank. The uranium and plutonium isotopic contents are measured. Samples of input solutions also contain fission products and some activation products. Because of this and due to the intense radiation, such samples are difficult to handle and analyse.

The separation of uranium, plutonium and the fission products at the nuclear reprocessing facility results in concentrated, rather pure solutions of U and Pu. The element content and isotopic composition of U and Pu are measured on samples from these 'product' solutions.The product solutions are used as base material for oxide powder production. The fissile isotope and element content of these UO_2 or PuO_2 or $(U,Pu)O_2$ samples are measured.

3. Information Requested

The analytical requirements depend on the sample characteristics and type of nuclear facility providing the samples. As already indicated in the previous chapter, a variety of samples of different chemical and physical properties have to be analysed. The information requested usually focuses on the one hand, on the uranium isotopic composition, whereas the ^{235}U isotope abundance is the most relevant information for safeguards purposes. The uranium content (or concentration) in a sample also needs to be determined. The combination of the latter with the mass of the sample, the mass of the bulk and the ^{235}U abundance allows the total amount of fissile uranium to be calculated. If information on the plutonium element content is required, the plutonium isotopic composition also needs to be known. The combination of results of the sample with the declarations on the bulk provide the total amount of plutonium.

The ^{241}Am concentration, relative to the amount of Pu, allows conclusions on the time of the last plutonium separation to be made [11, 12].

The facility types, material types and analysis types typically encountered in the fuel cycle are summarised in Table 1. The third column specifies the sample sizes taken for verification measurement purposes. They are

specified, such that, the uncertainties arising from sampling are kept to a minimum [13, 14]. It has to be emphasized that the amount of material actually required for a measurement can be considerably lower.

Table 1: Simplified overview of facility categories, material types, desirable sample sizes and analyses.

Facility Type	Material	Sample size [13]	Analysis
Enrichment	UF_6	4-8 g	U conc., U iso.
Fuel Fabrication	Solution: UO_2^{2+} nitrate solution	20 g	U conc., U iso.
	Pu nitrate solution Powder: UO_2	1-5 g	Pu conc., Pu iso.
	PuO_2	10 g	U conc., U iso.
		3 x (1-5 g)	Pu conc., Pu iso., Am conc.
	Pellets: UO_2	7-20 g	U conc., U iso.
	MOX	2 x (5-10) g	U conc., U iso.
			Pu conc., Pu iso., Am conc.
Reprocessing	Solution:Spent Fuel	1-5 g	U conc., (U iso.)
			Pu conc., Pu iso.
	UO_2^{2+} nitrate solution	10 g	U conc., (U iso.)
	Pu nitrate solution	1-5 g	Pu conc., Pu iso.

4. Sample Analysis Methodology

For any of the quantities to be determined as mentioned in Table 1, a selection of analytical techniques is available and several of them can be applied to attain the desired goal. The choice of the measurement method depends on:

- sample composition,
- available amount of material, which may be limited due to activity or dose rate restrictions, sample transport regulations and sampling procedures at the facility,
- desired measurement uncertainty,
- instrumentation and manpower available,
- tolerable measurement delay,
- creation of (secondary) waste and
- costs of the analysis.

Whatever the method of choice might be, there are always advantages and disadvantages. Methods enabling a higher accuracy may require higher investment and/or running costs or may be more demanding in terms of operator skills and analysis time. This evaluation should in any case be done in the light of the analytical needs, the available resources and the desired degree of "fitness for purpose". The list of methods presented below is neither exhaustive nor is it intended to describe a preference in any form. However, it covers most of the techniques currently being used.

4.1 Element Assay

The determination of the assay (concentration or content) of uranium and/or plutonium is of key importance for establishing the material balance in a facility for accountancy and verification purposes. It is therefore essential to have a method at hand that allows the respective element concentrations to be measured in samples taken at the facility. Classical chemical methods compete with methods based on physico-chemical or purely physical principles. Whatever principle is applied, the analytical goal is the quantitative measurement of the amount of uranium or plutonium in a sample. The different techniques applied may require different ways of sample conditioning (e.g. dissolution, dilution, special geometry).

4.1.1 Titration

Titrimetric measurements are carried out by determining the volume (or mass) of a solution of accurately known concentration (the titrant), which reacts quantitatively with the solution of the substance to be determined (the titrand). The point at which the reaction is just complete is called the equivalent point or stoichiometric end-point.

This end-point can be indicated by

- the potential between an indicator electrode and a reference electrode (potentiometric titration)
- the change in electrical conductivity (conductometric titration)
- the current, which passes through the titration cell between an indicator and a reference electrode (amperometric titration)
- the change in absorbance of the solution (spectrophotometric titration)

Uranium can be determined by potentiometric titration using the so-called “Davies and Gray” method [15, 16]. It is based on the reduction of uranium(VI) to uranium(IV) in concentrated phosphoric acid solution in the presence of sulfamic acid by reaction with iron (II) sulfate. The excess of iron(II) is subsequently oxidized by nitric acid in the presence of molybdenum. The uranium(IV) is determined by mass titration with standardized potassium dichromate solution to a potentiometric end-point. Interferences are to be expected from bromide, iodide, chromium(III), silver(I), tin(II) and vanadium(IV) and (V).

Plutonium can also be determined by potentiometric titration, using the so called “silver oxide” method [17]. First the plutonium is quantitatively oxidized with silver(II) oxide. The excess of silver is destroyed by adding sulfamic acid. The plutonium(VI) is then reduced to plutonium(IV) with an excess of iron(II) sulfate. The excess is titrated with potassium dichromate solution. Interferences are observed from V(V), Mn(II), Am and Np.

4.1.2 Coulometry

Coulometry is considered to be a reliable method for the determination of uranium and/or plutonium [18, 19, 20]. This method does not require a reference material for calibration, as it measures electrical charges and time. Coulometry is consequently a “primary method of measurement”. It has, furthermore, the potential of being highly precise and accurate. However, reference materials are required to verify the proper working of the instrumentation and to measure small offsets in the determination of the end-points.

The uranium determination by controlled potential coulometry calls upon the reduction of uranium(VI) to uranium(IV) at a mercury electrode in sulphuric acid. A potential of -0.325V is applied for the reduction reaction. The amount of uranium is calculated from the number of electrical charges (Coulombs) required to complete the reaction. The end-point of the reaction is reached when the residual current (background) is a few μA. Corrections have to be applied for the blank current and the background. Interferences may arise

from impurities such as copper, iron and manganese. This method is difficult to apply and used only infrequently.

The determination of plutonium applies the oxidation/reduction of plutonium between its oxidation states +3 and +4 in sulphuric acid. Reduction is performed at a potential of +0.270 V, while the oxidation step requires +0.670 V. Interferences may arise from iron present in the sample solution [21]. Coulometry is only applied in a few laboratories for routine verification measurements.

4.1.3 Gravimetry

The gravimetrical determination of uranium and plutonium is based on the assumption that calcination of a sample of either element will lead to a (stable) compound of defined stoichiometry. Uranium is heated in air or oxygen at 950°C in order to obtain U_3O_8. Similarly, plutonium is heated in air or oxygen at 1250°C in order to obtain PuO_2. If prepared under these conditions, the compound has been demonstrated to be stable and no deviations from stoichiometry are expected. This compound is then easily weighable and the element content in the initial sample can be calculated. Corrections have to be applied for impurities contained in the sample, as they will cause systematic errors. Hence, gravimetry always requires an impurity determination. The latter may be achieved by glow discharge mass spectrometry (GDMS), spark source mass spectrometry (SSMS) or inductively coupled plasma mass spectrometry (ICP-MS).

Gravimetry is also a "primary method of measurement". As it requires only weighing data and information on the sum of impurities, its potential for precision and accuracy is unsurpassed.

4.1.4 K-Edge Densitometry

Uranium or plutonium can be determined in a sample by K-Edge Densitometry (KED) [22]. The method uses a highly collimated X-ray beam passing through a sample solution of well-defined path length. Its transmission is measured as a function of energy in critical energy regions. The underlying measurement technique is the K- or L-shell absorption-edge spectrometry, colloquially called K-Edge Densitometry. The abrupt change of the transmitted X-ray intensity at the K absorption edge is a measure of the uranium or plutonium concentration in the sample. The K-Edge instrument requires a series of carefully characterized solutions of uranium and/or plutonium for establishing a calibration curve. More recently, the calibration curve was established by a point calibration (reference solution) in combination with Monte-Carlo calculations [23].

K-Edge Densitometry can be applied to uranium or plutonium solutions from 25 g/L up to saturation (approx. 400 g/L). Interferences arise only from elements having their K absorption edge in the same energy region as the element under investigation. Consequently, the simultaneous presence of uranium and plutonium needs to be taken into account and an appropriate correction has to be applied. K-Edge Densitometry delivers measurement results as volume concentration, i.e. in milligrams per millilitres or grams per litre. Most other techniques deliver results as mass fraction, i.e. in milligrams per gram. Consequently, one needs to determine the density of the solutions under investigation in order to be able to compare the measurement results obtained by the different techniques.

4.1.5 X-Ray Fluorescence

An X-ray beam of higher energy stimulates the emission of characteristic X-rays from uranium and plutonium (X-ray fluorescence, XRF). The intensities of the induced X-rays may be used for the determination of the U/Pu ratio in a sample or, after an appropriate calibration, for the absolute determination of the respective amounts of the elements. In the first case the U/Pu ratio is derived from the net peak areas of the UKα_1 and

the PuKα_1 X-rays. The latter case calls upon the peak area measurement of the K$\beta_{1,3}$ lines of uranium and plutonium. Interferences are to be expected from any X-ray or soft lines of similar energy. Furthermore, the self-absorption in the sample has to be taken into account.

4.1.6 Isotope Dilution Mass Spectrometry

Isotope dilution analysis (IDA) is based on the addition of a known amount of an enriched isotope (called the "spike") to a sample [24, 25, 26]. After equilibration of the spike with the sample, mass spectrometry is used to measure the altered isotopic ratio(s), therefore named isotope dilution mass spectrometry (IDMS). The amount content of the element under investigation can be derived from the change(s) in isotope ratio(s) and known amount of spike added. Consequently, only weighing of the sample and spike mass and measurements of ratios of the sample and sample-spike mix (of ion beam intensities) have to be performed. The actual measurement is performed after equilibration of spike and sample and chemical separation of the element of interest. This assures the removal of isobaric interferences and a smooth ionisation process.

Uranium samples are usually spiked with ^{233}U, an isotope which is not present in the sample. Therefore, a single measurement allows the uranium content and the isotopic composition of the sample to be simultaneously determined. Also enriched ^{235}U or ^{236}U are used as spike isotopes; this however requires independent measurements of the ratios in the unspiked and the spiked sample.

Plutonium samples can be spiked with ^{244}Pu, an isotope which is usually not present in the sample. Due to its very limited availability, the use of this isotope has been restricted to exceptional cases. Mostly, plutonium samples are spiked with enriched ^{242}Pu. The application of ^{239}Pu or ^{240}Pu as spikes has been demonstrated successfully [27]. However, spiking with ^{239}Pu, ^{240}Pu or ^{242}Pu requires independent measurements of the ratios in the unspiked and the spiked sample as well.

IDMS is a highly selective method and has the potential for high accuracy and precision. Also IDMS could be considered a "primary method" of measurement under special measurement conditions.

4.1.7 Spectrophotometry

Spectrophotometry is based on the principle of absorption of light (in the ultraviolet, visible or near infrared range) as a function of wavelength. Absorption peaks indicate the presence of a certain element in a particular electronic configuration. The peak intensity is a measure of the species' concentration. If an element concentration has to be measured, all species of this element have first to be brought to the same oxidation state.

Spectrophotometry can be applied to the determination of Pu. As hexavalent plutonium has the highest molar extinction coefficient, the best results are obtained by measurement of Pu(VI). The achievable precision of this technique is limited to the percent range; the accuracy depends on the completeness of the oxidation to Pu(VI). Spectrophotometry is usually applied as a simple and rapid method for process control, it is rarely used for accountancy or verification purposes.

4.1.8 Inductively Coupled Plasma Mass Spectrometry

As pointed out above, the determination of chemical impurities plays an increasingly important role in nuclear safeguards. The sum of impurities (metallic and non-metallic elements) is important for the gravimetric determination of uranium or plutonium compounds. On the other hand, the pattern of chemical impurities may point to the chemical process used for producing the uranium or plutonium compound. Trace elements can be determined by a variety of methods, such as optical emission spectroscopy, atomic absorption spectroscopy, glow-discharge mass spectrometry or inductively couples plasma mass spectrometry (ICP-MS).

The latter is the most prominent technique and offers high sensitivity in combination with good selectivity. ICP-MS can be applied to basically all metallic elements in the periodic table and also to some non-metallic elements. The characteristic feature is the fact that a plasma (typically an Argon plasma) at a temperature of 5000-8000 K serves as an ion source, with the sample usually introduced as a fine mist (produced from the sample solution which passes a nebulizer and the subsequent spray chamber sorts out the larger droplets) allowing only fine droplets to pass into the plasma. Like all mass spectrometric techniques, the instruments sorts the ions produced in the plasma according to their mass to charge ratio and measures the respective ion current. The latter is proportional to the relative abundance of the corresponding species in the sample solution. One of the challenges in multi-element analysis by ICP-MS is isobaric interferences. Careful experimental design and appropriate corrections, however, minimizes the impact on the results (i.e. reduces bias). Obviously, ICP-MS can also be used for isotope ratio measurement.

4.2 Isotope Assay

Besides the determination of the element concentration (or content), the measurement of the isotopic composition of uranium and plutonium is of interest. This is due to the fact that the elements, uranium or plutonium are not fissile per se, but rather their isotopes with uneven mass numbers (e.g. ^{235}U, ^{239}Pu). Despite this fact, plutonium is regarded as a fissile material, irrespective of its isotopic composition. In contrast to that, safeguards authorities pay particular attention to the uranium isotopes ^{235}U and in special cases to ^{233}U.

The accurate determination of the isotopic composition of U or Pu is of prime importance for verification purposes. Different measurement techniques based on different measurement principles are available for this purpose. The choice of the method depends on the requested accuracy, the nature of the material and other factors as discussed already earlier.

4.2.1 Thermal Ionisation Mass Spectrometry

Mass spectrometry is the most commonly used technique in nuclear safeguards [28] (see also section 4.1.6.) for measuring the isotopic composition and isotopic amount content (by IDMS) of uranium, plutonium and other actinides in a sample [26]. Thermal Ionisation Mass Spectrometry (TIMS) is widely applied for isotopic measurements [29]. An example of such mass spectrometer is shown in Figure 1.

A sample preparation step prior to the actual measurement is required. This consists of the separation of the element of interest from other elements (e.g. matrix materials or impurities). The sample is then deposited onto a filament from which it is evaporated after being introduced into the mass spectrometer. The sample vapour is then atomized and at the hot (>1600 0C) filament surface, ionised from which the name “thermal ionisation” is derived. The species U+-ions are accelerated by applying high voltage and subsequently separated according to their mass to charge ratio. An appropriate detection system allows the measurement of the ratios of the ion beam intensities. The isotope abundances are derived from these ratios.

TIMS relies on chemically purified samples in order to avoid isobaric interferences. TIMS is therefore very selective and can measure isotope ratios with low uncertainties.

Figure 1: Triton Thermal Ionisation Mass Spectrometer (Thermo Fischer Scientific, Bremen, Germany).

4.2.2 Gas Source Mass Spectrometry

Samples, in the form of UF_6 could only be measured by TIMS after hydrolysis and elimination of the fluoride ions. The application of an ion source suitable for gas measurements, however, allows the direct measurement of uranium hexafluoride by gas-source mass spectrometry (GSMS). The ionisation is achieved by electron impact. The species measured is UF_5^+, consequently the masses to be measured are at positions 330 ($^{235}UF_5^+$) or 333 ($^{238}UF_5^+$).

GSMS has a high potential for precise and accurate measurements. It is mainly applied at the enrichment facilities, facilities for accountancy purposes; and occasionally for safeguards verification measurements [30].

4.2.3 Gamma Ray Spectrometry

For the sake of completeness non-destructive analytical methods are also mentioned in this paper, since they are often combined with destructive analytical methods. Radiometric methods can be applied for isotope assay, but they are limited to non-stable isotopes emitting either α-particles or gamma rays.

The most prominent is certainly gamma ray spectrometry. It uses the characteristic gamma lines, or more precisely, the energy of the gamma rays emitted from a particular isotope. Their intensity is a measure of the number of atoms present in the sample. It is applied in a variety of instrumental and software modifications. Detectors of different geometries (facilityar, coaxial, dwell) and prepared from different materials (NaI(Tl), Si(Li), Ge(Li), high purity silicon, high purity germanium, Cd(Te) are in use. The type of detector to be used is selected depending on the application, the desired spectral energy resolution, the efficiency and the useful energy range. A number of computer codes have been developed for spectral deconvolution, for data reduction and evaluation [31, 32]. Gamma spectrometric methods have considerably improved in performance over the last years. They are widely applied for accountancy and verification measurements [6].

4.2.4 Alpha Spectrometry

Alpha spectrometry uses the discrete energy of the α-particles emitted by certain radioactive isotopes for the identification and quantification of the respective nuclides. It requires the careful preparation of thin layers of the analyte. The resulting α-spectrum allows the activity ratio of the α-active isotopes present in the sample

to be measured. The isotope abundance ratios can be derived from that. Its application in safeguards is limited to the determination of the $^{238}Pu/^{239+240}Pu$ ratio. This information is complimentary to the information on the $^{238}Pu/^{239}Pu$ ratio obtained by mass spectrometry, which sometimes suffers from isobaric interference of ^{238}U.

This method is often applied for screening Pu aliquots after chemical separation and before TIMS measurements, for the presence of ^{238}U and ^{241}Am.

4.3 Combined Methods

It is evident that the methods discussed so far can, to some extent, be combined. Powerful measurement methods may result, often enabling increased sample throughput, reduced operator radiation doses and more efficient laboratory work. Combined methods usually rely on physical measurement principles, which are applicable at the same time.

4.3.2 COMPUCEA

The combined procedure for uranium concentration and enrichment assay (COMPUCEA) calls upon a combination of gamma ray spectrometry for measuring the ^{235}U abundance and L-Edge Densitometry for the uranium concentration measurement. The methods involved have been discussed in some detail in the sections above. Instead of the K-Edge, the L-Edge adsorption edge is used. Applications of the instrument are in verification measurements at enrichment facilities, at fuel production facilities and for the uranium product streams of reprocessing facilities [33, 34, 35]. COMPUCEA setup is shown in Figure 2.

Figure 2: COMPUCEA – Combined Procedure for Uranium Concentration and Enrichment Assay.

4.3.3 Hybrid K-Edge / K-XRF Densitometry

The combination of K-edge Densitometry with X-ray fluorescence results in the so-called Hybrid K-Edge (HKED). This instrument applies a single X-ray source for both parts of the analysis, the K-Edge absorption and the fluorescence excitation. It has proven to be an extremely useful analytical tool in the verification of reprocessing input solutions. It is also applicable to mixtures of uranium and plutonium. The combination of

the two techniques allows the simultaneous and quantitative determination of uranium and plutonium. This can even be done directly from samples of highly radioactive input solutions [36].

4.3.4 Neutron Coincidence / Gamma Counting

Neutron coincidence counting relies on the spontaneous fission on ^{240}Pu and the neutrons produced with each fission process. The neutron count rate is a measure of the amount of ^{240}Pu present in the sample. However, accurate information on the isotopic composition of the sample is required in order to correct for neutron contributions from other Pu isotopes (^{238}Pu and ^{242}Pu) and to calculate the total amount of plutonium.

If applied in combination with high resolution gamma spectrometry, a complete plutonium assay in solid samples (MOX or PuO_2 powder) is possible [37, 38]. The method is mainly used by the Euratom inspectors in field for safeguarding Pu and MOX production.

5. Analysis of Samples for Verification Purposes

The analysis of samples for verification purposes needs to meet the three safeguards goals:

- Goal **Q**uantity
- **T**imeliness,
- Characteristic **P**robabilities (alpha, beta) risk of false alarm or non-detection

Q.T.P. determines the number of items to be verified. The Euratom Q.T.P. is intended to ensure an efficient and effective safeguarding of nuclear material [39]. Table 2 lists Q.T.P. for material under safeguards verification:

Table 2: Euratom Q.T.P.

	Material type					
	^{235}U in LEU	^{235}U in HEU	NU, DU	Pu-fresh	Pu (irradiated)	Th
Goal Quantity	75 kg	25 kg	10 t	8 kg	1 fuel assembly	20 t
Timeliness	1 y	1 m	1 y	1 m	3 m	1 y
probability	Alpha ≤ 0.05 and beta ≤ 0.1					

On the laboratory level measures have to be taken to make sure that these requirements can be met. This implies certain requirements for the laboratory on the analytical method applied, such as:

- reliability and traceability of measurement results,
- uncertainty of measurements results,
- laboratory delay,
- efficient use of resources,
- sample throughput.

These measures comprise organisational, infrastructural and scientific/technical arrangements. It means that laboratories performing sample analysis for verification purposes have to demonstrate that they deliver reliable and traceable measurement results which are "fit for purpose" within the required measurement uncertainties in compliance with the International Target Values for Measurement Uncertainties in Safeguarding Nuclear Materials (ITVs) [14]. These are uncertainties to be considered in judging the reliability of analytical techniques applied to industrial nuclear and fissile material, which are subject to safeguards verification. The values represent estimates of the 'state of the practice' which should be achievable under routine measurement conditions or during actual safeguards inspections.

The vast majority of Euratom safeguards verification samples are analysed under the responsibility of the European Commission – Joint Research Centre – Directorate G – Nuclear Safety and Security, G.II.8 Nuclear Safeguards and Security in Karlsruhe, Germany (JRC-Karlsruhe). These analyses are carried out during in-field measurement campaigns at the site being inspected, and at the two On-Site Laboratories (Sellafield and La Hague). Off-site analyses are carried out at the laboratories at JRC-Karlsruhe. Selected Euratom samples in the form of UF_6 are analysed with GSMS at the European Commission – Joint Research Centre – Directorate G – Nuclear Safety and Security, G.II.5 - Nuclear Data and Measurement Standards in Geel, Belgium (JRC-Geel) [40]. Others samples are analysed in field by the Euratom inspectors themselves.

5.1 Field Measurements

5.1.1 In-Field Measurements

In-field measurement campaigns are carried out either with transportable equipment (exclusively on uranium samples to avoid the transport of Pu-contaminated equipment) such as COMPUCEA or on installed Euratom equipment in nuclear installations, such as neutron gamma counting. COMPUCEA covers the needs arising in uranium handling facilities, whereas Neutron gamma counting covers Pu and MOX facilities. It is suitable for verification measurements during physical inventory taking (PIT) by the inspectors. Hence, in-field measurements are an excellent tool for near real-time verification measurements. More recently, the COMPUCEA has become the method of choice for supporting physical inventory verifications (PIV) in fuel fabrication facilities and its application has been extended towards in-field analysis of UF_6 in enrichment facilities [41].

5.1.2 On-Site Laboratories

Safeguarding the large reprocessing facilities undoubtedly poses a challenge to the Safeguards Authorities. The size of the facilities and the high material throughput require a significant effort in verification activities. Furthermore, uranium and plutonium product samples in the form of nitrate solution or as oxide and also U/Pu mixed oxide need to be analysed. Thus, an important area of in-field measurements covers the verification analyses of reprocessing input solution samples. In order to achieve the required high level of detection probability, the safeguards inspectors need to take a large number of samples, several hundred a year, which have to be subjected to independent analysis. Evidently, the results of these analyses need to be highly reliable, reporting times have to be short, costs have to be kept at a reasonably low-level and waste production should be kept to a minimum.

Based on these aspects, the Euratom Safeguards Office (ESO) decided in the early 1990's to develop, install and operate safeguards analytical laboratories at the two large European reprocessing facilities, namely the 'On Site Laboratory (OSL)' at Sellafield (UK) and the 'Laboratoire sur Site (LSS)', at La Hague (France) [42]. Measurements at these on-site laboratories are carried out using HKED, TIMS, IDMS and high-resolution gamma spectrometry. The common goal of the team of analysts – using the state of the art measurement

equipment available in the laboratories – is to deliver measurement results at a constantly high quality. In order to achieve the above-mentioned goal a systematic concept for analytical quality control was developed and implemented. The use and correct application of certified reference materials (CRMs), quality control samples, performing replicate measurements, comparing results from different analytical techniques, participation in external quality control and rigorous data and document control are the pillars of any analytical quality control system [43]. The quality control concept implemented in the on-site laboratories forms an integral part of the laboratories' measurement strategy, see also section 7.

5.2 Off-Site Analysis

The analysis of samples in the laboratory (off-site) represents certainly the ideal case from the measurement point of view. Optimal measurement conditions can be achieved, profiting from a well-developed infrastructure and technical support. The (sometimes lengthy and costly) transport of samples from the nuclear installation to the safeguards laboratory is the downside of this approach.

5.2.1 Measurement Techniques and Instrumentation

In the JRC laboratories the measurement techniques and instrumentation listed below are routinely applied for verification sample analysis. It should be noted that, for radiation safety requirements, some of the instruments need to be adapted for glove-box or hot-cell use. It should furthermore be noted that manufacturers, brands, types of instruments are mentioned here for the sole purpose of illustration and should in no way, neither directly nor indirectly, be considered as a recommendation.

- potentiometric titration: several autotitrators are available for this purpose (Mettler Toledo, Mertrohm, Hach-Lange, Radiometer)
- thermal ionisation mass spectrometry (TIMS): Finnigan MAT 262, Spectromat TIBOX and Thermo Fisher Triton sector field mass spectrometers are available
- gas mass spectrometry: Uranus GSMS sector field gas mass spectrometer from Thermo Fisher
- isotope dilution mass spectrometry: sample preparation is performed in a glove-box supported by fully or partially automated chemical separation systems (based on ion exchange resins or extraction chromatography) and measurements are either performed by ICP-MS or TIMS
- neutron coincidence counting combined with gamma spectrometry, a specially developed instrument is used
- K-Edge Densitometry, a specially developed instrument combined with off-the-shelf parts
- Hybrid K-Edge, a specially developed instrument combined with either ORTEC or Canberra parts
- COMPUCEA: a specially developed combination of L-Edge densitometry and gamma spectrometry is used
- alpha spectrometry: several devices from Canberra and Ortec

In addition to the techniques mentioned above, other methods are available (e.g. ICP-MS, SIMS, GDMS, electron microprobe, electron microscopy, X-ray diffraction, Electron spectroscopy for chemical analysis - ESCA-, etc.). These techniques, however, are not routinely applied to safeguards verification samples. In special cases, like the analysis of vagabonding materials, some of these methods will be applied in addition.

5.2.2 Verification Sample Analysis

Reprocessing input samples are typically analysed for isotopic composition and uranium and plutonium element concentration. This is achieved by TIMS and by IDMS, respectively.

The concentration of uranyl and plutonium nitrate solutions are determined by K-Edge Densitometry. Density measurements have also to be performed for reasons given already earlier (see section 4.1.4). If the solutions are too dilute for applying KED, they are measured by IDMS. The isotopic composition is determined by TIMS.

Powder samples of uranium oxide (UO_2, UO_3 or U_3O_8) are first checked for sample mass in order to correct for possible weight changes due to moisture uptake during transport. Then these samples are dissolved and subjected to potentiometric titration, K-Edge and/or COMPUCEA. The isotopic composition is typically determined using TIMS.

PuO_2 powder samples are treated similarly. As a supplementary technique the high resolution gamma spectrometry is applied to these samples prior to dissolution. In this way information on the ^{241}Am content is obtained in addition to the total Pu content in the sample.

Samples of uranium and plutonium mixed oxide powder are first checked for weight change. The further treatment of pellets and powder samples is identical. The uranium and plutonium contents are measured as well as ^{241}Am concentration using the combined neutron/gamma counter or in a combination of gamma spectrometry, and after dissolution, Hybrid K-Edge determination of the uranium and plutonium. Further aliquots are used for isotopic measurements of U and Pu by TIMS.

6. Environmental Sampling and Special Samples

Special samples, are samples, taken by inspectors under special conditions or for special purposes under the provision of the Additional Protocol (AP). Destructive analytical methods and techniques are often the methods of choice to determine the elemental content, the isotopic composition and the impurities of such special samples. Impurity analysis can confirm the consistency between materials and declared processes giving evidence that only declared materials are present at a facility.

Analysis of environmental samples is carried out to detect traces in the environment originating from technological activities. The AP authorizes safeguards authorities to verify the absence of undeclared nuclear activities in all parts of a state's nuclear fuel cycle, including uranium mines, fuel fabrication facilities, enrichment facilities and nuclear waste sites, as well as any other location where nuclear material is or may be present, and this at nearly any time. Environmental sampling has been routinely applied for about 20 years and is recognised as a sensitive and reliable tool for the verification of the absence of undeclared nuclear activities.

The most common "environmental" samples are swipe samples. These samples are taken by inspectors wiping over surfaces (such as floor, pipework, sampling points etc.), mainly in enrichment and reprocessing facilities. These swipe samples are shipped for analysis to the IAEA's laboratories in Seibersdorf, Austria and the Network of Analytical Laboratories (NWAL) [44]. Upon arrival, the swipe samples are screened for uranium, plutonium or other actinides using gamma spectrometry or X-ray fluorescence. The sample preparation consists of the removal of particles from the cotton swipe by either a liquid extraction procedure or a vacuum impactor technique. Once the particles of interest have been identified and localized, isotopic measurements are performed. These particles typically show a diameter of a micrometer or less, hence containing only picogram amounts of material. To determine the isotopic composition, the following instrumental techniques (Table 3) can be applied [45]:

Table 3: Typical sample types and measurands encountered in "environmental" sample analysis.

Sample Type	Measurand	Instrument Type
U-oxide particles	Elemental composition Particle morphology	Scanning electron microscopy + X-ray spectrometry
U or U-oxide particles	Isotopic composition	SIMS (directly) FT-TIMS (fission track) TIMS (if loaded on filament) ICP-MS (using laser ablation)

6.1 Secondary Ion Mass Spectrometry

A SIMS (Secondary Ionisation Mass Spectrometry) instrument sputters and ionises a sample by ion bombardment from a primary ion beam. The ionised material is extracted and analysed in a mass spectrometer. A SIMS instrument is capable of analysing all elements in the periodic table, at trace levels. The application for particle analysis for nuclear safeguards purposes requires that the SIMS instrument has an ability to find the particles of interest (e.g. U and Pu particles) in a matrix of other materials as well as to perform precise and accurate measurements of the isotopic of both major and minor isotopes [46, 47].

Recently, the performance of SIMS instrumentation for nuclear particle analysis has greatly improved, thanks to the implementation of Large Geometry - SIMS (LG-SIMS), the CAMECA IMS 1280 (Figure 3), 1280-HR or 1300-HR rather than the previously used SG-SIMS instruments. LG-SIMS instruments feature numerous instrumental advantages, in particular removal of background interferences with minimal loss of transmission, and parallel detection of all U isotopes using the multi-collection system. In addition, the productivity has significantly increased with the implementation of an automated particle measurement (APM) software that performs fast screening of the sample to determine the exact location of the particles of interest and a first estimate of their isotopic.

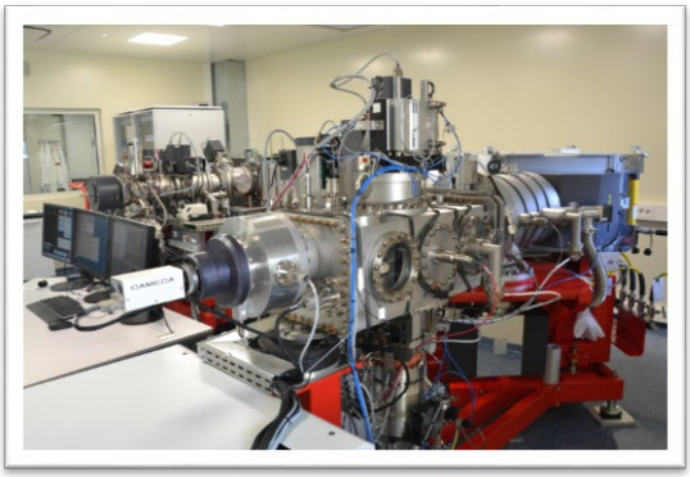

Figure 3: CAMECA IMS 1280 HR.

6.2 Thermal Ionisation Mass Spectrometry on Single Particles

TIMS measurements on individual particles offer the advantage of superior accuracy on the uranium isotope ratios. However, the sample preparation is more complex than for SIMS. A way to select the particles of interest is to apply scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX). In SEM, the produced electron beam is deflected in such a way that it raster scans a rectangular area of the sample surface. The energy exchange between the electron beam and the sample results in the emission of electrons and electromagnetic radiation, which can be detected to produce an image. An additional feature of SEM is the energy-dispersive X-ray spectrometer. This technique is based on the principle that the interaction of the electron beam with the sample allows the chemical composition of the sample to be determined by means of the characteristic X-ray lines emitted. SEM-EDX allows the morphology and the elemental composition of uranium particles found in dust sampled at nuclear facilities [45, 48, 49] to be characterised. The analysis of the isotopic composition of these particles involves the transfer of a single micrometer-sized uranium particle with a micromanipulator onto a TIMS filament [50].

6.3 Fission Track Thermal Ionisation Mass Spectrometry

Uranium particles for TIMS analysis are selected by irradiating the samples with neutrons in a nuclear reactor. A uranium-free piece of a thin film detector is attached to the sample and both are exposed to a flux of thermal neutrons. The resulting induced fission of the ^{235}U in the sample creates induced tracks in the external detector, which are revealed by etching. The number of fission tracks that is produced by the uranium particles indicates the level of ^{235}U enrichment [51]. Subsequently the selected particles are transferred onto a filament for TIMS measurements for isotopic composition analysis [51].

6.4 Laser Ablation Inductive Coupled Plasma Mass Spectrometry

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) has only been applied for the analysis of particles from environmental sampling for less than a decade. Laser ablation is the process of removing material from a solid surface by irradiating it with a laser beam. By means of laser ablation coupled to an inductively-coupled-plasma (ICP) ion source a single uranium particle can be ionised and its isotopic composition measured, most commonly, by applying an ICP-MS with a multi-collector detector system [52, 53, 54].

Environmental and special samples often pose to inspectors and analysts the problem of 'finding the needle in the hay stack'. In environmental sampling, it may be that only the combination of different environmental traces allows the absence/presence of undeclared activities to be confirmed. For special samples the aim is to have access to all information inherent to the material. Therefore, impurity measurements on special samples and accurate isotope ratio measurements, particularly of the minor uranium isotopes in environmental samples, but also in nuclear materials are of major concern to draw relevant safeguards conclusions. All the mass spectrometry techniques mentioned in section 6 are highly sensitive to impurity analysis (ICP-MS) as well as being capable of the determination of the isotopic abundances of not only ^{238}U and ^{235}U but also of the minor abundant uranium isotopes, ^{234}U and ^{236}U (ICP-MS, SIMS, TIMS) [55, 56]. Those elemental and isotopic fingerprints are a powerful tool to assess whether material is consistent with declared processes and to detect traces of nuclear material in the environment.

7. Quality Control and Confidence in Analytical Measurement Results

Accountancy and control of nuclear material require analytical measurements that "shall either conform to the latest international standards or be equivalent in quality to such standards" IAEA INFCIRC/153 [ ].

Nuclear safeguards conclusions are based to a large extent on comparison of obtained measurement results with the declarations of the operator [57]. Quality assurance (QA) and quality control (QC) in destructive sample analysis for nuclear safeguards measurements are the means to comply with the requirements to provide reliable measurement results for the nuclear safeguards system [58].

Confidence in the analytical measurement results provided by laboratories carrying out measurements for independent verification, for special sample analysis and in environmental sampling is on the basis of international political decisions in view of the peaceful use of nuclear energy and nuclear security.

QA and QC comprise different aspects:

- Method validation and instrument calibration,
- Traceability and comparability of measurement results,
- Uncertainty of measurement results,
- External performance evaluation,
- Document/data control and deployment of a quality system.

Measurement standards are an indispensable tool wherever measurements are carried out. Their fundamental role is to establish traceability of a measured value (i.e. the analytical result) to a primary unit of measurement as defined in the SI system. Only measurement results that are traceable to a common reference, namely the respective SI unit, can be regarded as truly comparable. In measurements of amount of material, these measurement standards are generally provided in the form of reference materials (RM). According to the definition in the International Vocabulary of Metrology – Basic and General Concepts and Associated Terms JCGM 200:2012 a reference material is defined as a material, sufficiently homogeneous and stable with reference to specified properties, which has been established to be fit for its intended use in measurement [59]. Such a reference material shall consist of "a material or substance which is homogeneous and for which one or more values are well established" [60].

Reference materials serve for calibration of a measurement instrument, for validation of a measurement technique and, to assess the reproducibility of measurement results. They are also used for the periodic assessment of a measurement system or for the assignment of values to materials [61]. Reference Materials need to be applied, in particular, for the quantitative verification of nuclear material as used in traditional safeguards, but also in other measurements, for instance, in environmental sampling. Elemental RMs are typically used to calibrate methods such as titration, coulometry or K-Edge Densitometry. Isotopic reference materials are applied to calibrate mass spectrometers. Spike reference materials are isotopically enriched materials that are certified for isotopic composition (isotope ratio, isotope abundance) and amount content. They are mostly applied for IDMS measurements. Particularly large-sized dried (LSD) spikes (Figure 4) of uranium and plutonium are applied for accountancy verification measurements of input solutions [62, 63].

Figure 4: Preparation of U/Pu mixed large-sized dried (LSD) spikes.

Reference materials, certified for isotopic amount content and/or isotopic abundance ratios, can be obtained from laboratories specialised in their certification in compliance with ISO 17034 [64], including the JRC-Geel [65], the NBL Program Office (NBL PO) in the United States [66], and the Commission for the Establishment of Analytical Methods (CEA/CETAMA) that resides within the French Atomic Energy and Alternative Energies Commission [67].

A 'trueness check' is part of a laboratory's method validation. This means comparing the measured value of a certified (matrix) reference material with the certified value given on the certificate, and to assess their compatibility to exclude any significant bias [59]. Secondary reference materials, also called 'working standards', are used as quality control samples that undergo, with a certain periodicity depending on the quality system, the same sample preparation and measurement procedure as the unknown sample.

Special attention has been given to the development of reference materials and quality control samples for the analysis of special and environmental samples. To meet these future needs, the JRC-Geel has produced a number of reference materials certified for minor uranium isotope ratios and is developing uranium reference particles for nuclear safeguards and non-proliferation control [68, 69].

Recently, the development of certified reference materials and quality control tools for "age" determination of nuclear materials has been successfully undertaken and will be further pursued. IRMM-1000a and IRMM-1000b, jointly produced in accordance with ISO Guides 34 and 35 by the JRC-Geel and the JRC-Karlsruhe, are uranium reference materials certified for the production date based on the $^{230}Th/^{234}U$ radio-chronometer, i.e. the date of the last chemical separation of these two radionuclides [70, 71]. These type of CRMs are not only required for proper validation of measurement procedures in nuclear, safeguards, but also in nuclear forensics and security in order to determine the 'age' of (seized) uranium samples and to provide traceability of the measurement results to the SI [72].

The uncertainty on the analytical result consists of the uncertainty from the certification of the RM, the uncertainties resulting from the repeatability of the measurement results and any systematic errors. The uncertainty on the quantitative verification of the accountancy of nuclear material includes, besides the uncertainty on the sample analysis, also the uncertainty on the bulk measurement and on the sample taken from this bulk. The International Target Values (ITVs) represent estimates of achievable uncertainties under routine measurement conditions. They are intended to be used by facility operators and safeguards organizations [14].

In nuclear safeguards the aim is to independently verify that operator's declarations are correct and that there are no undeclared nuclear materials or activities. An important part of this process is that measurement results provided by operators, safeguards laboratories and expert laboratories have to comply with specific

quality goals for nuclear material and environmental sample analysis to be translated into meaningful (safeguards) conclusions. External control of the quality and assessment of conformity of the measurements of the nuclear fuel cycle materials is indispensable to demonstrate measurement capabilities [73]. Participation of Euratom safeguards laboratories, the IAEA Network of Analytical Laboratories (IAEA-NWAL), and of operator analytical services in inter-laboratory comparison schemes is a perfect tool to evaluate their measurement performance and to compare analytical measurement results obtained with different analytical methods on samples from a single batch.

Since 1982 the JRC-Geel has organised the Regular European Interlaboratory Measurement Evaluation Programme (REIMEP) [74]. In REIMEP campaigns, samples matching materials analysed routinely in the nuclear fuel cycle are sent to participating laboratories for measurements, involving safeguards laboratories and more recently also environmental laboratories throughout the world. The certified test samples proposed to participants in REIMEP comparisons have ranged from UF_6, MOX pellets, U, Pu oxides to U, Pu nitrate solutions (Figure 5) [75, 76, 77].

IAEA Office of Safeguards Analytical Services (SGAS) also organizes Nuclear Material Round Robin exercises on a biannual basis, with an aim to assess the analytical performance of participating laboratories, including IAEA NWAL members, NWAL candidates and nuclear facility operator laboratories. Moreover, regular participation in the NMRORO rounds and contributing analytical data let the organizers capture the current "state-of-practice" in terms of analytical precision.

The Nuclear Signatures Interlaboratory Measurement Evaluation Programme (NUSIMEP) was established in 1996 to support the growing need to trace and measure the isotopic abundances of elements characteristic for the nuclear fuel cycle and present in trace amounts in the environment [78, 79, 80]. Participation in the NUSIMEP external quality control exercise enables participants to demonstrate and assess their ability to carry out precise measurements, in particular, on trace amounts of uranium and plutonium.

Laboratories participating in REIMEP and NUSIMEP are asked to perform the measurements working under routine conditions using the techniques, procedures and instrumentation of their own choice and report a result with a best estimate of the expanded measurement uncertainty. They have the possibility to benchmark their results against independent and traceable reference values. Individual measurement results of participants are compared to the certified reference value provided by the JRC-Geel. The certified reference value has a demonstrated uncertainty evaluated according to international guidelines and demonstrates traceability to the SI. Other regular inter-laboratory comparison providers are CETAMA [67] and NBL PO [66].

An essential part of a good quality system is to assure that analytical staff is well trained, that equipment is operational and suitable for the type of analysis that a decent project management is implemented and that data and documents are controlled and archived in a proper way. Since the Guide to the expression of uncertainty in measurement (GUM) is now more than 20 years old, staff performing analyses nowadays in a number of these laboratories have been educated to estimate their measurement results and associated uncertainties according to GUM and EURACHEM [81, 82, 83]. Analytical laboratories, particularly those performing nuclear material analysis for industry and/or safeguards authorities, are striving more and more towards accreditation under ISO/IEC 17025 or seek compliance with similar international/national standards [84, 82, 85], in order to have an external attestation by an accreditation body with regard to their technical abilities [86, 87]. Participation in inter-laboratory comparisons as part of a well deployed quality system enables laboratories to assess their measurement performance. At the same time, it allows laboratories to demonstrate their competence on a high quality level to accreditation, authorisation, and inspection bodies as well as to safeguards authorities.

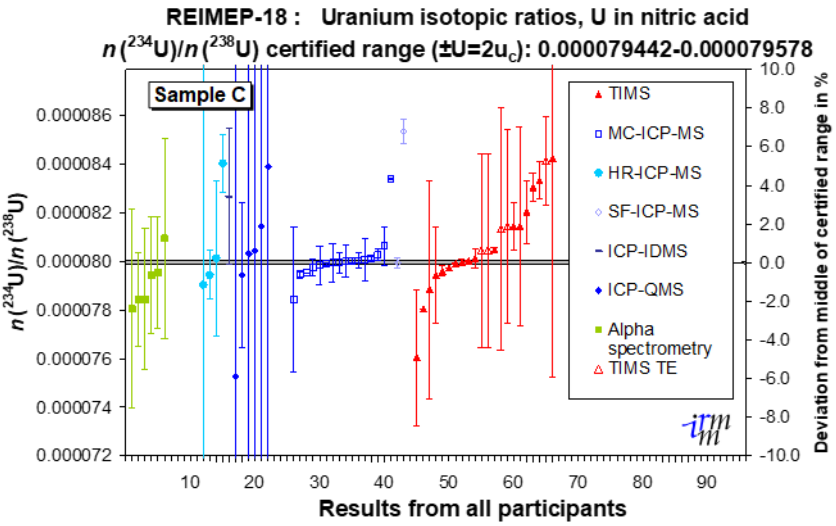

Figure 5: Participant results from REIMEP-18 'Isotopic abundances of low-enriched uranium in nitrate solutions.

8. Summary

Destructive Analysis (DA) is one out of many complementary measures applied in safeguards. DA is applied when highest sensitivity, accuracy and precision are required. Verification sample analysis activities can be performed on-site (either using mobile equipment in-field or in on-site laboratories) or off-site after shipment of samples to a specialized laboratory. Particularly in environmental sampling and for the analysis of special samples, destructive analysis is used to answer specific questions. Analytical techniques are applied, that are suitable for determining uranium and plutonium isotopic compositions in nuclear materials or environmental samples, as well as the respective element content or concentration. Experience with a number of these techniques has shown that effective analytical support to the safeguards authorities can be provided. Quality control and quality assurance is indispensable in order to provide reliable measurement results of high quality to safeguards authorities. This is also of major importance towards the convergence of nuclear forensics, environmental sampling and classical safeguards analysis.

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Nuclear Forensic Methods in Safeguards

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Abstract

The introduction of strengthened safeguards, the implementation of the additional protocol (INFCIRC 540) and the nuclear material intercepted from illicit trafficking led to a more investigative character of analytical measurements. The more specific questions will be asked with respect to a given sample, the more investigative analytical methodologies will be required and the more thorough, interpretative and comparative evaluation of results needs to be done. Specific applications, often in combination with only minute amounts of sample call for methods of high sensitivity, low detection limits, high selectivity and high accuracy. Consequently, the new sample types triggered the transfer of analytical techniques from the environmental area, materials science and geological or cosmological area to the safeguards community. The selection of the method or combination of methods is done according to the sample and information required. Data interpretation is calling for reference information, comparison samples and thorough understanding of the processes taking place throughout the nuclear fuel cycle. Environmental analysis and nuclear forensic science have experienced during last 20 years significant developments in the mentioned area which safeguards can profit from.

Keywords: strengthened safeguards, nuclear forensics

1 Introduction

Measurements of nuclear material were the backbone of the verification measures in the early days when the safeguards agreements, INFCIRC 153 and the EURATOM regulation 3227/76, were implemented. Consequently, measurement methods were put in place, which provided information on the uranium, plutonium or thorium content, as well as U and Pu isotopic compositions in a given material. These measurements served the verification of declared amounts of nuclear material. Apart from verification of the nuclear material accountancy, the information inherent to the nuclear material was never exploited.

When the International Atomic Energy Agency (IAEA) started introducing strengthened safeguards and the additional protocol was implemented, the mandate of the IAEA expanded from the verification of correctness of a state's declaration to comprise also the completeness of such declarations. The detection of undeclared nuclear activities or materials requires establishing a comprehensive picture of a state's nuclear activities and checking the consistency of the declarations against other evidence. In consequence, a tremendous need for information at different levels arises in order to enable the evaluation required.

All types of information sources can be drawn upon: e.g. satellite imagery, design information verification, on-site inspections and sample taking (comprising nuclear material samples and environmental samples). In the present paper, we discuss the challenges the strengthened safeguards approach brings along, as well as we describe how methodologies that were initially developed for nuclear forensic use could be exploited in safeguards.

2 Challenges

2.1 Information

Verification of the absence of undeclared nuclear material or activities is very complex task. The answer needs to be composed of a variety of indicators, which allow drawing conclusions on the completeness of state's declaration. The nuclear material and environmental samples taken, provide a useful source of information on the processes applied. Let us recall in this context two main prerequisites:

1. The production and processing of nuclear material leaves (inevitably) traces in the environment. Highly sensitive measurement techniques as applied in the IAEA's Environmental Sampling programme make use of this fact. Depending on the cleanliness of the process and on the quality of the installations, the amount of detectable traces can be rather small. Many years of experience gained in environmental sampling and, in particular in the analysis of single particles has demonstrated the power of this methodology. The main limitations of particle analysis are caused by the tiny amounts (few pico grams or even less) of material available in micrometer-sized particles. Moreover, the measurement of minor isotopes in individual particles may suffer from poor precision (due to counting statistics) and from molecular interferences.
2. Every production process leaves characteristic patterns in the material. These measurable parameters vary as a function of starting material, process parameters, reagents used, storage conditions or vessel materials. The complexity of the data and the interrelations between individual parameters require a careful step-by-step approach from measurement to data interpretation.

The information obtained through the analysis of nuclear material may be divided into two categories: **endogenic** data, i.e. data that is self-explaining (e.g. the $^{235}U/^{238}U$ ratio pointing at the enrichment of the material and the intended use), and **exogenic** data, i.e. data that can only be understood with the help of reference data (e.g. comparison against data from known material or from model calculations). The latter type of information is certainly more difficult to understand and requires more resources before a conclusion can be drawn. Chemical impurities, isotopic composition of the nuclear material, isotopic composition of accompanying elements and microstructure are data which are accessible through measurements and which allow to build information. The measurement information and their respective interpretation are expected to prove the absence of undeclared nuclear activities. The conclusion to be reached at the end of this evaluation process is based on "four C's":

- **Consistency** of information
- **Coherence** between samples or materials
- **Conformity** of findings with declared processes
- **Comparison** of data

In contrast to traditional safeguards, such an evaluation is not based on quantities of material, but rather on certain qualities of material such as impurities, age, stable isotopes and microstructure.

2.2 Measurement

The challenge in performing measurements of investigative character is twofold: first, a wide spectrum of parameters needs to be measured; and secondly, those parameters providing the most significant information need to be identified. The instrumental techniques applied for this purpose are well established, e.g. mass spectrometry, electron microscopy, anion chromatography. However, the analytical methods need to be adapted to the specific requirements of investigative safeguards analysis. For developing such methods, one

can benefit from experiences made in other fields of science, e.g. in nuclear forensics, isotope geology or material science.

2.3 Data Evaluation

In order to properly evaluate the measurement data, the availability of reference information is required, in particular for exogenic data. To some extent the safeguards community can draw upon experience and use the data available in the geochemical community. Variations in the isotopic composition of the chemical elements have been studied in other contexts and in some cases cadastral registers of isotopic data are available (e.g. $n(^{18}O)/n(^{16}O)$ ratio in rainwater or lead isotopes in natural lead). Information related specifically to nuclear material is, however, less widely available, e.g. data on metallic impurities in nuclear fuels are often subject to commercial confidence. In order to make best use of the additional information obtained through the methods, a comprehensive set of reference data or of reference samples (i.e. samples obtained from known sources and produced through known processes from known starting materials) needs to be established. In addition, a multidisciplinary team of analysts is required as the information arises from diverse scientific areas covering chemistry, physics and material science.

3 Characteristic Parameters

3.1 Isotopic Patterns of U and Pu

For long time the safeguards community has made use of the isotopic composition of nuclear material. Increased attention to the minor abundant isotopes in uranium (^{234}U and ^{236}U) was paid only after the introduction of strengthened safeguards, when the need arose to establish capabilities for distinguishing between samples of (apparently) the same enrichment. The isotope abundances of ^{234}U and ^{236}U may help to verify coherence between different samples and consistency with declared operations. The presence of small amounts of ^{236}U will indicate a contamination with recycled uranium and hence point at reprocessing activities. However, also in natural uranium variations in ^{236}U as well as in ^{234}U abundances have been recorded [1]. At ^{236}U abundance levels close to natural abundance (i.e. $n(^{236}U)/n(^{238}U) < 10^{-9}$) more sophisticated instrumentation, like Accelerator Mass Spectrometry is required [2]. This technique is available only in few specialized laboratories. In addition, different enrichment processes may result in slight differences in the ^{234}U abundance.

The isotopic composition of uranium and plutonium also allow drawing conclusions on the reactor type in which the material has been irradiated. Table 1 shows the results of isotope abundance measurements (three sub-samples) on a sample seized in the context of a criminal investigation. Comparing the measured values to burn-up calculations, it has to be noted that uranium and plutonium are not originating from the same reactor type: plutonium shows an isotopic composition close to an LWR reactor, while the uranium isotopic composition points at natural uranium fuelled research reactor.

Table 1: Isotopic composition of uranium and plutonium in a seized sample containing radioactive liquor. Measurement uncertainty UC (k=1) is given in brackets and refers to the last two digits of the isotope abundance.

Isotope	Isotopic Composition [Mass%]		
	Q1.1	**Q1.2**	**Q.1.3**
^{234}U	0.0159 (8)	0.0158 (8)	0.0158 (8)
^{235}U	0.3480 (70)	0.3501 (70)	0.3406 (68)
^{236}U	0.1383 (41)	0.1396 (42)	0.1361 (41)
^{238}U	99.497 (99)	99.494 (99)	99.507 (99)
^{238}Pu	1.316 (26)	1.315 (26)	1.321 (26)
^{239}Pu	59.66 (60)	59.61 (60)	59.87 (60)
^{240}Pu	28.19 (42)	28.25 (42)	28.06 (42)
^{241}Pu	5.30 (10)	5.29 (10)	5.32 (10)
^{242}Pu	5.51 (11)	5.52 (11)	5.42 (11)

The isotope correlation technique was used in safeguards in 1970's for two reasons: to verify the consistency of the isotopic analyses performed at the reprocessing plants, and to deduce the amount of specific isotopes by measuring other isotopes and using established correlations. Lately it was also adapted to nuclear forensics. In particular, the isotopic composition of plutonium is a useful indicator of the reactor type in which the nuclear material was produced. The neutron capture cross-section of the individual plutonium isotopes varies as a function of neutron energy. In consequence, the build-up of plutonium isotopes is different in reactors with different neutron energy spectrum. In addition, the initial enrichment of ^{235}U is various in different reactors. These two parameters are reflected in the isotopic composition of plutonium. Knowing the plutonium isotopic composition, we can draw conclusions on the reactor type, where the Pu is coming from (Figure 1).

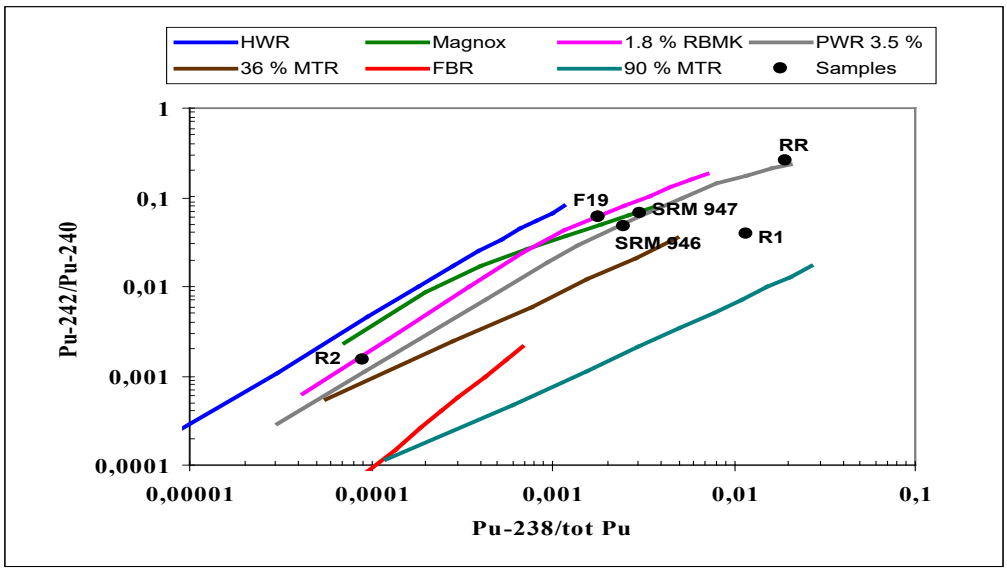

Figure 1: Pu isotope correlation for different types of reactors [3]. SRM 946 and SRM 947 (both are NBS certified Pu reference materials) originate apparently from pressurized water reactors, as well as sample RR used in a round robin exercise. F19 and R2 denote seized materials, which can be attributed to an RBMK reactor.

3.2 Age Determination

Age determination of nuclear materials makes use of the radioactive decay of these elements. Assuming a complete separation of the daughter products during the production process (e.g. during chemical purification of the material), we can determine the "age" (i.e. the time that has elapsed between the last chemical treatment of the material and today) of the material by quantifying the amounts of parent and daughter nuclides. Age determination of plutonium is classically being performed by gamma spectrometry using the $^{241}Pu/^{241}Am$ parent/daughter ratio. However, in a few cases it has been noticed that the Am separation has not been complete, thus the age from this parent/daughter may give a wrong answer. The use of the uranium daughters of ^{238}Pu, ^{239}Pu and ^{240}Pu offers a consistency check [4], as these three parent/daughter relations should result in the same age – provided the separation of uranium was complete during processing of the material.

Residual amounts of uranium isotopes will lead to biased results in the Pu age determination. The degree of the bias is dependent on the Pu composition (weapons or reactor grade Pu) as well as on the parent/daughter relation. Figure 2 shows the relative biases for the worst and best cases of Pu materials. The bias is a function of the age of the material (the older the material, the more U is produced and the less any residual uranium will affect the result) and of the amount of residual uranium after the last chemical separation of the plutonium (the more residual uranium is left in the plutonium sample, the higher the bias will be). As is seen from the model calculations, the parent daughter ratio can be very sensitive to residual amounts of uranium and thus lead to significant biases in the age determination (Figure 2b). The data in the model calculations were obtained by combining burn-up calculations, decay calculations and isotope mixture calculations.

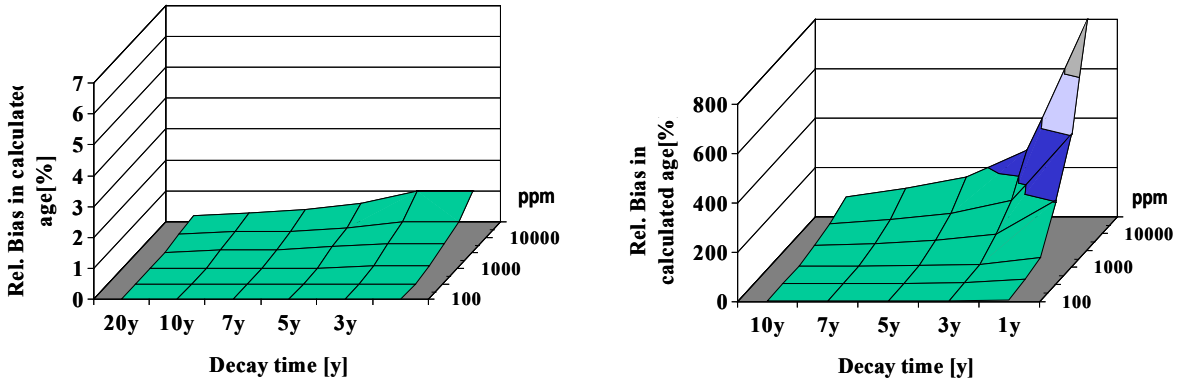

Figure 2: Relative bias in the age of reactor grade Pu (a) and weapons grade Pu (b) using the 238Pu/234U parent daughter ratio as a function of the age and of the amount of residual uranium [5].

For uranium age determination the parent/daughter relations $^{234}U/^{230}Th$ and $^{235}U/^{231}Pa$ are used. Age determination of uranium is somewhat more difficult than Pu dating, because of the considerably longer half-lives of uranium isotopes, which lead only to minute amounts of in-growing daughter nuclides. This means that the separation of Th and Pa from uranium must be of high chemical recovery and a highly sensitive measurement technique (such as TIMS, ICP-MS or alpha spectrometry must be applied [6]. The age of uranium can be determined also by direct measurement without chemical separation using the ICP-MS [7].

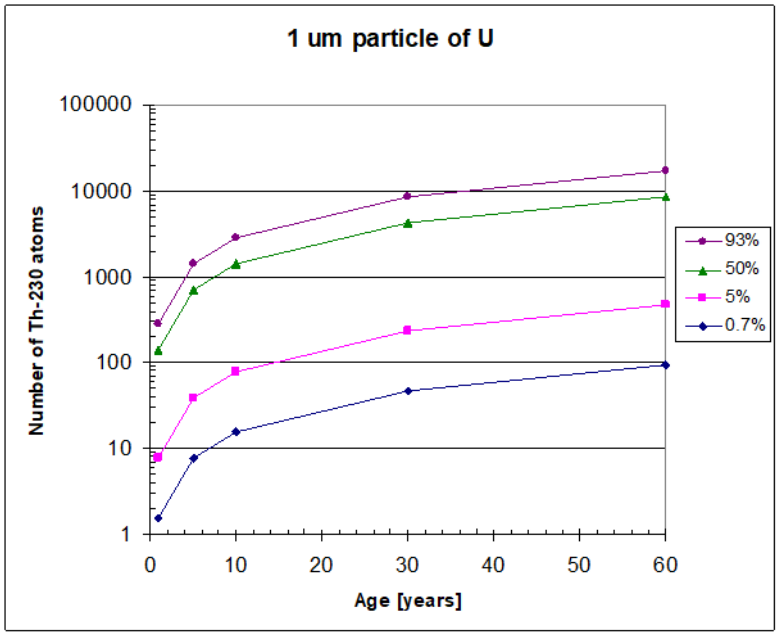

Figure 3: The decay of 234U produces 230Th. The number of 230Th atoms contained in a uranium oxide particle (with an assumed number of 1010 atoms of uranium) depends on the age of the particle and the initial enrichment.

Another interesting aspect in the age determination, especially in the safeguards context, is the question of the age of particles. Age determination of plutonium particles has been demonstrated earlier [8]. Age determination of uranium particles proves to be much more challenging, due to the very long half-lives of the uranium isotopes ^{234}U and ^{235}U. Even if the ^{234}U is the lower abundant isotope in U materials, due to the 1000-fold shorter half-life the parent daughter ratio ^{234}U/^{230}Th is more favourable ratio for the age determination of the uranium than is the ^{235}U/^{231}Pa ratio.

The particles of interest in swipe samples from enrichment plants are typically only one micrometre in diameter. Based on this assumption, we can calculate the detection limit for the age determination as a function of the age of the particles and the ^{235}U enrichment. Assuming further a detection efficiency of 0.5% (i.e. for detection of 10 ions we need 2000 atoms) in the secondary ion mass spectrometer, we see from Figure 3 that age determination can only be successfully performed for particles of highly enriched uranium.

3.3 Metallic Impurities

Metallic impurities are present in nuclear material samples at varying concentration levels. In starting materials (e.g. uranium ore) the impurities may have the character of accompanying elements and are present in relatively high concentrations. In intermediate products (e.g. uranium ore concentrates) the concentration of most of the chemical impurities has been drastically reduced. After this, towards the final product, further decrease of impurities is minute if any. Figure 4 shows metallic impurities in natural uranium compounds of different origins. Five samples from the same origin can be clearly recognized through their identical pattern of metallic impurities.

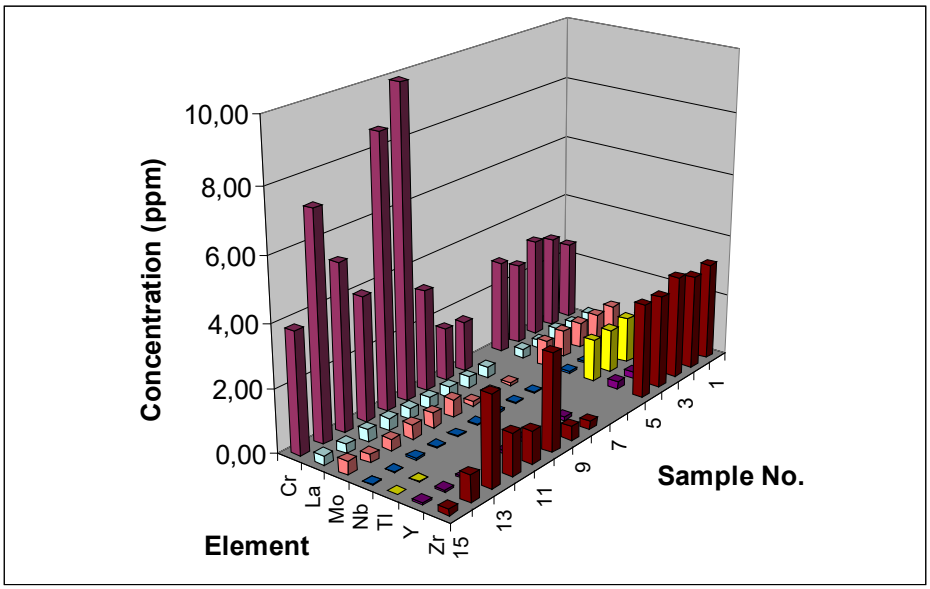

Figure 4: Selected metallic impurities in intermediate natural uranium products. Samples 1 to 5 are apparently of the same origin.

Although metallic impurities can be used for identifying coherences between samples or batches of material, the systematics behind the impurity patterns are not well understood. This is because the metallic impurities may be carried into the material at different stages of the process [9]. The concentration of some impurities may for instance vary as a function of exposure time to the container material or the storage tank, as they are leached from the surface of the walls. In sample analysis the concentration of such elements appears to be fluctuating randomly. One should, in general, avoid the use of common elements as indicators. Another solution to this dilemma could be, instead of looking at the absolute concentrations of impurities to look at ratios of chemical elements. While the absolute concentration of the impurities may change, the ratio of certain elements will vary only within narrow limits. This applies in particular for elements of similar chemical behaviour, e.g. the rare earth elements, which have characteristic patterns in relation to the type of uranium ore they are originating from [10].

3.4 Stable Isotopes

In the field of food science and geochemistry, analysis of stable isotopes (e.g. ^{1}H, ^{2}H, ^{12}C, ^{13}C, ^{16}O, ^{18}O) have been successfully applied for a few decades. The principle of the use of stable isotopes is very straightforward: The stable isotope compositions of elements, which are part of a substance, are a function of the origin and history of that substance. That is, two substances which are chemically the same may have different stable isotope compositions if either their origin and/or history differ. This methodology was also introduced recently to nuclear forensics.

The application of oxygen isotope ratio measurements for geolocation purposes has been demonstrated several years ago. A correlation between the geographic location of the production site of uranium oxide samples and the variation in the $n(^{18}O)/n(^{16}O)$ could be established [11]. Moreover, it could be shown that the method is also applicable to individual particles, i.e. the oxygen isotope ratios established by "bulk" measurements using thermal ionisation mass spectrometry (TIMS) could be reproduced on individual particles using secondary ion mass spectrometry (SIMS) [12]. This type of information does obviously not identify a specific plant, yet it provides a parameter for attributing the material to a region. This can be utilised for instance to distinguish between imported and domestic materials.

Another parameter that has been widely used in geochemistry and in environmental sciences is the isotopic composition of lead. Lead isotopes may be primordial (natural lead) or they may be produced through the decay of uranium isotopes. The small variations in the isotopic composition of natural lead have been used to locate the origin of some fuel additives (mainly consisting of tetra-ethyl lead). The adaptation of this methodology for nuclear safeguards and nuclear forensics purposes has been studied [13]. It could be shown that the lead isotopic composition of yellow cake provides useful information to distinguish between natural uranium materials of different origins (Figure 5). As lead is omnipresent in our environment, special care has to be taken when performing the chemical separation of the lead from the uranium samples in order not to introduce any natural lead from dust particles or chemical reagents and thus bias the results.

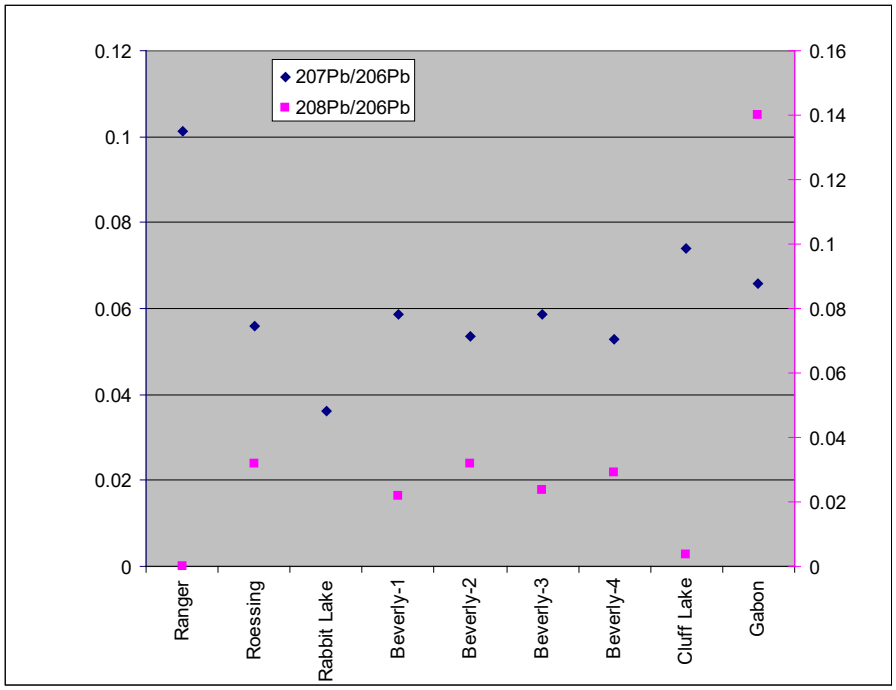

Figure 5: Lead isotope ratios observed in yellow cake samples from different mines [13]. Combined uncertainties, Uc (with k=2) on the ratios n(207Pb)/n(206Pb) and n(208Pb)/n(206Pb) are between 0.000 2 and 0.000 08, thus too small to be visualized on the above graph.

Lead is often used as shielding material for nuclear samples. This may introduce bias in the results as natural lead from the shielding cross-contaminates the lead contained in the sample. There are two possibilities for dealing with this problem: first, one can correct for all contributions from natural lead using the ^{204}Pb as pilot isotope. ^{204}Pb is not contained in radiogenic lead, and may therefore serve as indicator for the amount of natural lead present in a sample. The second option requires the availability of a reference sample from a suspected origin. In this case isotope mixture calculations can be performed, assuming a binary mixture between natural lead and the lead contained in the reference sample. An example is given in Table 2, where a seized uranium ore sample had been wrapped in a lead foil. The isotope mixture calculation showed that the measured isotopic composition can be fully explained by a binary blend of natural lead and the lead (as measured before) in uranium ore from Joachimsthal (Czech Republic).

Table 2: Lead isotope abundances (mole-%) of a seized uranium ore sample (Find-25) and of natural lead. The lower line shows the results of a blending calculation, assuming a mixture of 56% natural lead and 44% lead from uranium ore from Joachimsthal mine.

Sample	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb
Find-25	1.20	33.27	19.32	46.20
Nat. Pb	1.4	24.1	22.1	52.4
Joachimsthal	0.96	45.12	16.56	37.36
Mixture 56/44	*1.21*	*33.36*	*19.67*	*45.78*

Also other elements with useful stable isotope ratios (e.g. Sr, Nd, S), have been studied to see how the ratios propagate during the processing starting from U ore up to calcined U_3O_8 powder [9]. The study showed that while Pb is the most sensitive element for cross-contamination from environment, reagents etc., also Sr ratio suffers from the issue, although with lesser extent. As shown in Figure 6, after the U leaching from the ore, the $^{87}Sr/^{86}Sr$ ratio remains relatively constant. However, the link back to the original ore has been lost.

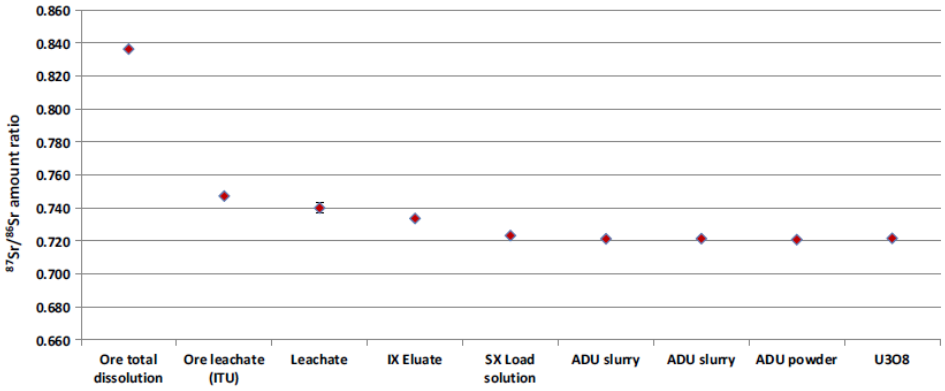

Figure 6: Propagation of the 87Sr/86Sr ratio during uranium processing.

3.5 Anionic Impurities

Aqueous processing of nuclear material is encountered at a number of stages in the nuclear fuel cycle. In these processes mineral acids are frequently used. They leave anionic impurities (e.g. Cl^-, F^-, SO_4^{2-}, NO_3^-) in the material behind, together with those anions that were initially present in the starting material. We have studied such anionic impurities in yellow cake samples from different origins. Depending on the type of ore from which the uranium was extracted and the type of process applied as well as the associated chemical reagents used, the isotopic patterns generated in the yellow cake are significantly different. These patterns provide additional information for distinguishing materials from different origins or – if appropriate reference data is available – for relating a given material to a specific facility. For data evaluation, the pattern of anionic species is more informative than the actual concentration values. Figure 7 shows examples of chromatograms obtained from yellow cake samples from Germany and Gabon [14].

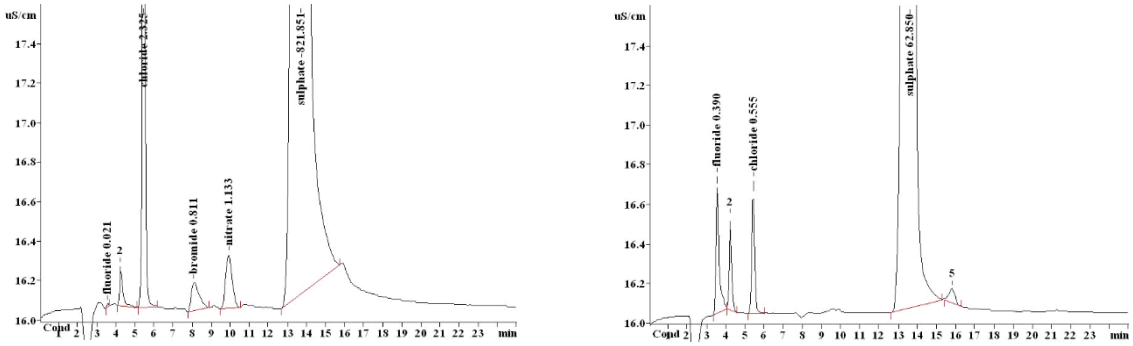

Figure 7: Anionic impurities in yellow cake samples from a German mine (a) and from a Gabonese mine (b) by ion chromatography.

3.6 Microstructure

Very little use has been made of microstructural information of nuclear materials in safeguards. This can be understood by the nature of the information, i.e. such information is essentially of qualitative character. Still the particle and grain size distributions and the surface structure of the particles are material characteristics that reflect the production process of the material. These data allow the direct comparison of samples enabling conclusions on coherence between samples. Figure 8 shows a comparison of four UF_4 samples. The particles are shaped and sized very differently, thus they can be clearly distinguished from each others, indicating different origins of the four samples in question.

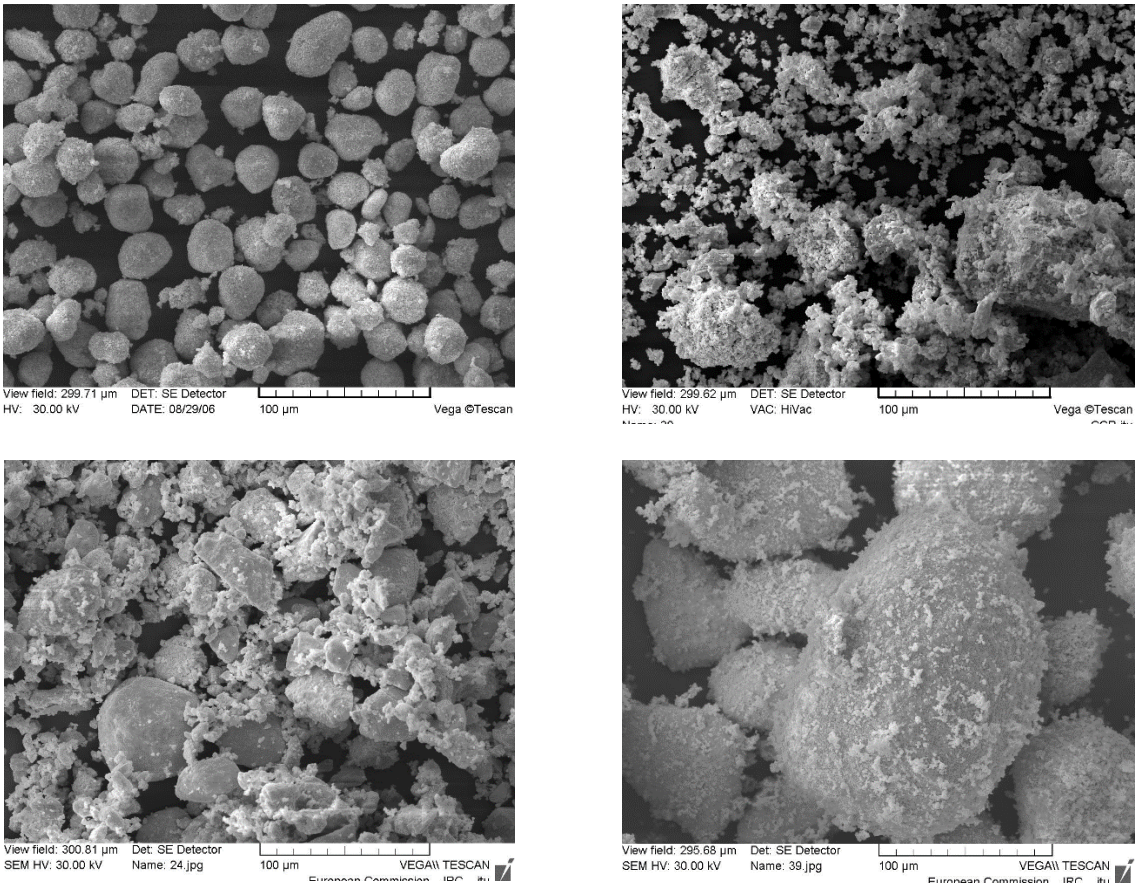

Figure 8: Comparison of microstructure in four UF4 samples.

4 Conclusions

The challenges associated with strengthened safeguards call for more investigative analytical methods. The verification of treaty compliance according to comprehensive safeguards agreements and the additional protocol are associated with a tremendous need for information. Part of the information required for the evaluation of the completeness of a state's declaration is inherent to the nuclear material. Advanced and investigative measurement methods, such as applied in nuclear forensics, need to be introduced in nuclear safeguards. Consequently, we will see a convergence of nuclear forensic and of classical safeguards analysis.

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Containment and Surveillance – Status and Perspectives

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1 Introduction

With the goal to timely detect a diversion of a significant quantity (SQ[91]) and to detect a misuse of a declared nuclear facility, the safeguards inspectorates from the International Atomic Energy Agency (IAEA) and EURATOM (EC) rely, inter alia, on a variety of containment and surveillance equipment. Those measures mainly based on optical surveillance (Figure 1) and sealing systems, can provide indications for possible diversions of nuclear materials or misuse of nuclear facilities, and their role is considered complementary to nuclear materials accountancy.

Figure 1: Safeguards surveillance systems monitoring a reactor hall (courtesy: IAEA, Vienna).

Present generations of nuclear facilities such as power and research reactors, commercial reprocessing and fuel fabrication plants, long term intermediate storage and conditioning facilities require highly automated and customized safeguards systems based on C/S techniques thus enhancing the role of C/S.

[91] Nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. For further information see chapter "Safeguards Approaches, Concepts and Measures"

2 Legal Basis of Containment and Surveillance /1/

The EURATOM Treaty of 1957 /2/ requires the European Commission to satisfy itself that, in the territories of the Member States, nuclear material is not diverted from its intended purposes as declared by the users. EURATOM Safeguards are applied to all civil nuclear material in all EURATOM Member States. Apart from the fact that the Treaty does not discriminate between nuclear weapons states and nonnuclear weapons states, nuclear material is the key objective suggesting inspections and accountancy as the measures of fundamental importance.

The Non-Proliferation Treaty (NPT) of 1968 /3/ requires (only) the non-nuclear weapons states to accept IAEA safeguards on all nuclear material in all peaceful nuclear activities with the view to preventing diversion to any nuclear explosive devices. According to Art. III para. 1 it is assumed that the peaceful activities may be carried out within the territory of a Member State, under its jurisdiction, or under its control anywhere. Again, it is the nuclear material that is in the focus.

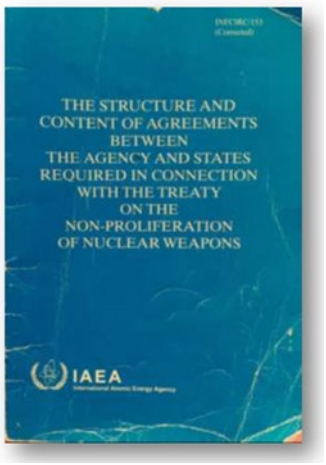

Figure 2: INFCIRC/153 (Corr.) (courtesy: IAEA, Vienna).

As all states party to the EURATOM Treaty are also member states of the NPT, the EURATOM and Agency safeguards systems had to be coordinated in order to avoid unnecessary duplication of safeguards. The Commission, the Agency and the non-nuclear weapons states of the EURATOM Treaty concluded the Verification Agreement (VA) known as INFCIRC/193 derived from the template INFCIRC/153 (Figure 2).

Finally, details of safeguards implementation in all EURATOM member states are laid down in EURATOM Regulation no. 302/2005. Art. 6, para. 2(e) of this regulation states that the Commission uses Particular Safeguards Provisions to establish, among others, C/S measures according to the arrangements agreed upon with the person or undertaking concerned. According to Art. 6, para. 1 also consultation with the relevant Member State is required.

It is interesting to note that on this basis the Commission is entitled to cooperate directly with the facility operators, whereas the Agency has to cooperate with the governments.

The VA assigns C/S measures a very prominent role as stated in Article 29:

"For the purpose of achieving the objective set forth in Article 28, material accountancy shall be used as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures."

Furthermore, the VA allocates the following functions and relevance to C/S:

- Use shall be made, for example, of containment as a means of defining material balance areas for accounting purposes (VA, Art. 7(b)).

- C/S shall be used to concentrate measurement efforts at key measurement points (VA, Art. 46 (b)(ii)).
- C/S may be applied and used by the IAEA as part of its inspections (VA, Art. 74(d)).
- The IAEA may apply its seals and other identifying and tamper-indicating devices to containments (if so agreed and specified in the Subsidiary Arrangements) (VA, Art. 75 (e)).
- The IAEA may install its own surveillance equipment (if so agreed and specified in the Subsidiary Arrangements) (VA, Art. 75 (d)).
- The actual number, intensity, duration, timing, and mode of routine inspections, among others, are correlated to the criterion 'degree of containment [of nuclear material]' (VA, Art. 81 (c)).

From these provisions it can be seen that C/S were intended to perform important functions right from the beginning. Regarding the integrity of containments, C/S are intended to register anomalies in the absence of inspectors as opposed to diversions of nuclear material. Furthermore, well-applied C/S can provide continuity of knowledge (CoK) of nuclear material flows and inventories and thus can make a facility more transparent and inspection activities in a facility more cost-effective and possibly less intrusive.

The VA constitutes nuclear material accounting as a fundamentally important safeguards measure, complemented by (C/S) measures. In many situations, the application of C/S is the best means to permit the safeguards objectives to be achieved at acceptable costs and with minimum intrusion into facility operations.

3 Containment and Surveillance Techniques /4/

Containment and surveillance techniques are extensively used by the IAEA and EC. The two main C/S categories are optical surveillance and sealing systems. The most important aspects of C/S measures are the monitoring of movement of nuclear material, interference with containment, tampering with (unattended) safeguards equipment and preservation of previously obtained measurement results, thereby reducing the need for re-measurement /5/. An often used example for an implementation of C/S systems in light water reactors (LWR) with spent fuel ponds located within the reactor containment building is shown in the schematic representation below. More examples and a more detailed description can be found in /6/.

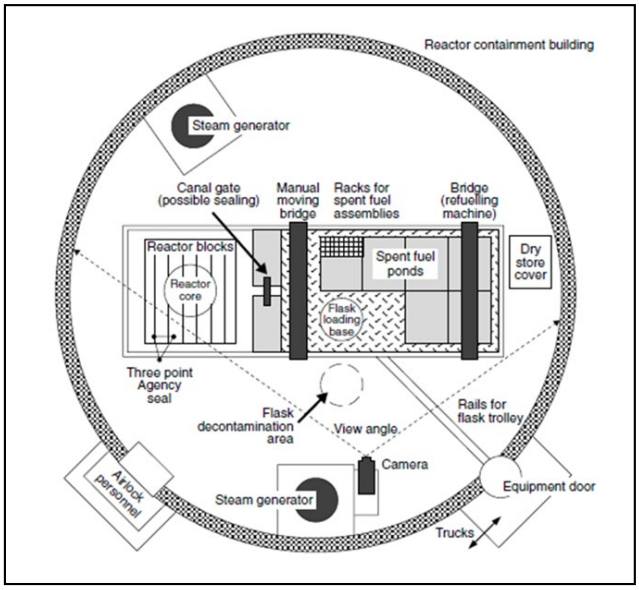

Figure 3: C/S measures implemented in a LWR (courtesy: IAEA, Vienna) /6/.

Due to the principally unattended use of C/S techniques, the functional requirements are very specific; however, depending on application they may also be facility-specific. The device must be reliable in the sense that it functions without failure during the intended inspection period, e.g., during an inspector's absence of several months. The reliability criterion requires a specified environmental qualification. The recorded data must be authentic, i.e., falsified data must be recognizable. That is why authentication implies tamper-indicating functions. For timeliness reasons in situ verifiability is of great advantage. Inspection effort can be significantly reduced if remote interrogation and verification functions are realized. Regarding seals, this is also true for archival functions, because seal data are archived upon seal application and retrieved for comparison upon re-verification. In general, the ease of evaluation of results and their conclusiveness are important requirements. The ease of use is another factor, as the inspectors have to carry out many different types of activity including the handling of measurement systems, seals, and optical surveillance systems. In addition, ease of use may be relevant in cases where facility operators agree to take over supporting activities in the absence of the inspector. Two more criteria have gained importance as microprocessor-controlled equipment is deployed: Recording capacity and integration capability. As inspection periods may be extended, the amount of data to be stored will increase, and different C/S devices are being integrated into C/S systems with new capabilities, such as the integration of video surveillance and electronic sealing, radiation monitoring and flow monitoring.

3.1 Surveillance

Optical surveillance should replace inspector presence and survey the path of nuclear material (in the facilities. It is most effective in storage areas, such as spent fuel storage ponds, with relatively few plant operator's activities that could be interpreted as movement of nuclear material. A typical application would consist of two or more cameras positioned to completely cover the storage area. The field of view of the cameras is such that any movement of items that could be the removal of nuclear material is easily identified. This means that items have to be sufficiently large within the field of view to be identified and that, preferably, at least two images have to be recorded during the movement of material. The image recording should be set at a periodic frequency (time lapse (TL) to allow the check of proper working of the camera) and maybe a motion (i.e. scene change) detection may trigger the recording, but a lot of experience is necessary for the set up. If TL is used alone the PTI (Picture Taking Interval) should be significantly shorter than the fastest possible removal time. But these techniques require a lot of experiences and tests during setup in field to avoid missing scenes so that in almost all cases a fixed PTI will be used.

Optical surveillance is intrinsically an unattended technique that may be enhanced by the remote data transmission (RDT) of image or the system "State of Health", which is the operational status of the surveillance system. But RDT capabilities means also that the data are authenticated and maybe encrypted before they are leaving the surveillance core component (SCC, i.e. the camera) so that nobody can falsify the information without detecting it during review.

Surveillance includes both human and instrument observation. As it is prohibitively expensive to arrange for permanent inspector presence, the EC and IAEA have acquired a range of optical surveillance systems that can provide effective, ongoing surveillance when an inspector is not physically present on site. Unattended optical surveillance techniques are used widely by the IAEA and EC to support and complement nuclear material accountancy and to provide CoK about nuclear materials and other items of safeguards' significance between on-site inspection visits.

Optical surveillance can be used to record images only, or it may be integrated with other unattended monitoring equipment that provides nuclear measurement, containment history and other data. The surveillance systems can also automatically transfer data to EC and IAEA Headquarters or to a regional office. Surveillance equipment is designed for the following basic applications:

(a) Single and portable camera systems for easy to access locations,
(b) Single or dual camera system for difficult to access locations (separate camera/s),
(c) Multi-camera systems for larger and more complex facilities,
(d) Short term and portable surveillance system for activities that include open core monitoring,
(e) Underwater cameras for applications in fuel storage ponds.

Surveillance equipment has evolved from film cameras (Minolta), through systems based on videotape technology (PSU, MIVS, Digiquad/Uniplex and MOS System), via the first digital systems (Gemini, FAST – based on commercial devices) and the custom designed Digital Image Surveillance (DIS) to today's NGSS (Next Generation Surveillance systems). The evolution of surveillance equipment has been mandated mostly by strong commercial trends that dictate the availability of applicable technologies on the market. With a significant reduction in the number of moving parts, DIS and NGSS are inherently more reliable than previous film and videotape technologies. Other benefits include improved authentication and encryption and its facilitation of RDT, radiation tolerance (single event upset (SEU) mitigation), enhanced battery, storage and State of Health capabilities.

The Digital Image Surveillance (DIS) System Based on DCM 14

In 1995, the IAEA and EC embarked upon a replacement programme to phase out old and obsolete surveillance equipment. In 1998, the Department of Safeguards decided that surveillance systems based on the custom designed DCM 14 digital camera module (Figure 4) met essential user requirements for the surveillance systems and that they were the most suitable equipment for the replacement of the existing film and videotape based systems. While very compact, the DCM 14 performs many tasks required for a modern safeguards surveillance system, including:

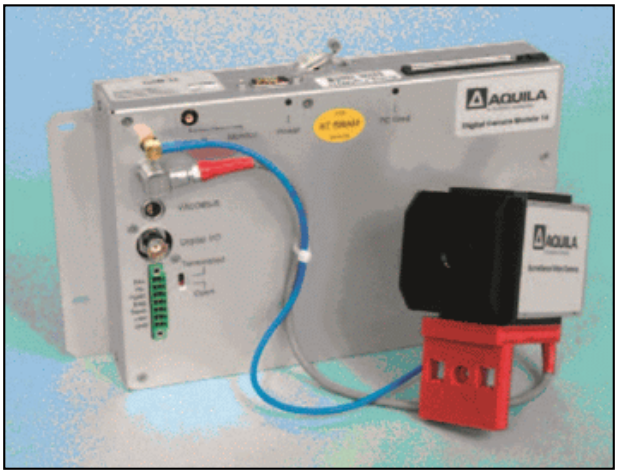

Figure 4: DCM 14 with video CCD camera (Charge Coupled Device) (courtesy: IAEA, Vienna).

(1) Digitization of a standard video camera image;
(2) Image and data authentication, ensuring genuineness, essential for RDT;
(3) Image and data encryption, ensuring confidentiality, important for RDT;
(4) Image compression to reduce image and data storage requirements (4GB = 240.000 images);
(5) Local storage to ensure redundancy when data are transmitted out of the camera housing;
(6) Detection of changes in the camera's field of view (scene change detection, SCD);
(7) Power management to ensure longest (several weeks) possible operation should the local facility's power fail;
(8) Secure remote surveillance when connected to a communications server via RDT.

Safeguards surveillance systems are relatively unique in that the equipment must operate unattended for extended periods in harsh conditions (i.e. under radiation) and with a high degree of security, power autonomy and reliability. Commercial off-the-shelf equivalents are not available. Systems that nearly meet the requirements invariably require some degree of modification, if technically possible.
Because of its inherent flexibility, the introduction of the DCM 14 also provided a means to consolidate and standardize future surveillance systems. Using the DCM 14 in different configurations it became possible to assemble single and multiple camera systems for easy and difficult to access locations from a standard array of basic building blocks. Since 1998, the DCM 14 has been used to construct 5 basic digital surveillance systems (ALIS, DSOS, DMOS, ALIP, SDIS) meeting the full range of safeguards applications, often in difficult environments (Table 1).

NGSS

The Next Generation Surveillance System (NGSS) was an important safeguards development in cooperation with the German (camera and interface) and United States (multi camera system and review) Support Programmes, which was initiated in March 2005. The first phase of the NGSS project focused on the conceptual design of the system, especially on the development of the Surveillance Core Component (SCC, here DCM C5, Figure 5) comprising the design of candidate hardware architectures, selection and irradiation testing of crucial components, prototype design, and performance evaluation /7/. In phases I and II an appropriate digital signal processor was selected; firmware prototypes were designed for performance evaluation and a functional design prototype of the SCC was demonstrated.
For the technology the following features for the camera unit were deemed crucial:

- enhanced authentication, encryption and transmission security by using public key infrastructure (PKI - more than 10 key pairs), improved radiation tolerance (SEU mitigation), enhanced tamper indication, picture taking at higher frequencies, image and data transport over Ethernet or high speed RS485 connection with TCP/IP protocol, colour imagery, 4 virtual cameras, which can have different fields of view,
- Improved storage capacity by using commercial SDXC card technology in digital camera module,
- Enhanced power autonomy for more than a month (PTI = 1 min), and
- Special Operating system for stronger hacker attack resistance due to full RDT capability /8/.

Figure 5: XCOH with DCM C5 with standard lens (fish eye lens with 180 degree angle of view is also mountable) and half size battery mounted in standard blue enclosure (courtesy: EURATOM, Luxembourg).

Table 1: Optical Surveillance Systems.

Code	Equipment name	Description and applications
Digital Surveillance Systems (Gemini, FAST, DSOS, DMOS phased out)		
FAST	FAST (later NICE) multi camera surveillance system	Up to 64 CCTV cameras connected via NV8 digitisers to a redundant PC based DVR
ALIP	All In One Surveillance Portable	Single camera system for easy to access locations and/or for portable surveillance applications, battery powered for 100 days
ALIS	All In One Surveillance	Single camera for installation in easy to access locations, mains or 24V powered
DSOS	Digital Single-Camera Optical Surveillance	Single camera system for installation in difficult to access locations, redundant recording by DCM 14 HW with other software
DMOS	Digital Multi-Camera Optical Surveillance	Multiple camera surveillance system for up to 16 cameras with remote monitoring capability
SDIS	Server based Digital Image Surveillance	Multiple camera surveillance system for up to 8 cameras with remote monitoring capability
XCAM	NGSS-ALIS (ALIS and ALIP replacement)	DCM C5 with AC power supply, display and Li-Ion battery for > 1 (or 3) months with PTI = 1 (or 3) min
XVID	NGSS-camera (IAEA) for multiple camera systems	XCAM without display as separate camera module for multi-camera systems
XCOH (see Figure 5)	NGSS-camera (EURATOM) for multi camera systems	NGSS Camera (DCM C5 and half size battery) in "Old" Housing, 24V power
XSOS	NGSS Small Optical Surveillance system (DSOS replacement)	DCI (Digital Camera Interface) for 1 or 2 DCM C5 or 14 in DSOS/MIVS housing
XMOS	NGSS Multiple Optical Surveillance system (DMOS replacement)	Display, DCI, DCS (Dual Comport Server) in a 19" rack and redundant power supply for 32 XCOH
XDIS	NGSS Multiple Optical Surv. system (SDIS replacement)	Display, DCI and power supply for up to 8 cameras
XWME	XMOS (EC) in 19" Wall Mounting Enclosure	Display, DCI, DCS in a 19" rack and power supply for up to 32 XCOH
Surveillance review systems		
GARS	Gemini (later General) Advanced Review Station	For Gemini, DIS (DCM 14) and partly XCAM recorded images, phasing out.
NGSR	Next Gen. Surveillance Review	State of the art development for NGSS and DCM 14 recorded images, integrated in iRAP (Integrated Review and Analysis Package)

Installed Single Camera Systems for Eeasy to Access Locations

ALIS. The All In one Surveillance unit (Figure 6) is a mains operated, fully self-contained digital surveillance system based on the DCM 14 digital camera module. It consists of a camera surveillance video component (SVC) (front), a video terminal VT 100 (left), the DCM 14 digital camera module with a backup battery for up to 5,000 image taking (right side) and a mains operated power supply (in the middle). All the components fit within a blue standard IAEA camera enclosure with all the functionality of the DCM 14 plus an integrated inspector interface terminal VT 100 for full system setup and check. Images and associated log files are stored on PCMCIA flashcards. With a 4 GB flashcard installed, ALIS can record between 240,000 and 360,000 images, depending on the compression used.

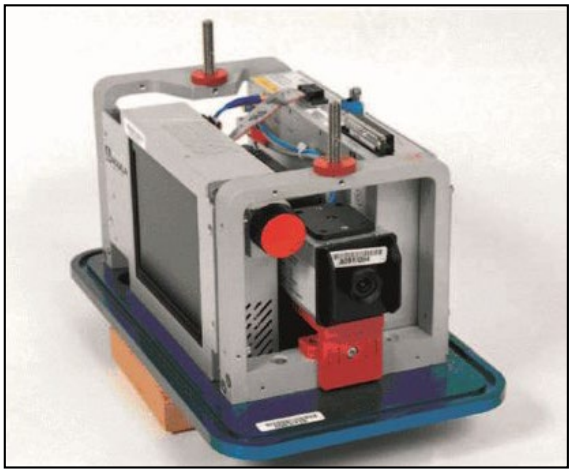

Figure 6: ALIS: All In one Surveillance unit (courtesy: IAEA, Vienna).

ALIP. The All In One Surveillance Portable unit (Figure 7) is a battery operated, fully self-contained digital surveillance system based on the DCM 14 digital camera module. It is an ALIS with a set of batteries on top, all of which are enclosed in a camera housing that has the same footprint as the standard IAEA camera housing but has been extended vertically to accommodate the batteries. With fully charged batteries, the system can perform surveillance duties for up to 100 days with no external power. Therefore, it will be used also for short term surveillance.

Figure 7: ALIP: All In One Surveillance Portable unit (courtesy: IAEA, Vienna).

XCAM: Based of the experiences with the ALIS the XCAM was developed as a successor for ALIS and ALIP between 2007 and 2010 (HW). The SCC is the DCM C5, which contains everything that is needed to take and store authenticated and encrypted images in a fully self-sealing and tamper resistant housing. On a 32 GB SD card (see on top of C5) more than a million colour images can be stored. The battery capacity allows a power autonomy for taking more than 50,000 images (more than 3 months with a PTI of 3 min) and the display DCD which can be turned in all directions to allow the full setup and check of the XCAM via a jog-dial (Figure 8).

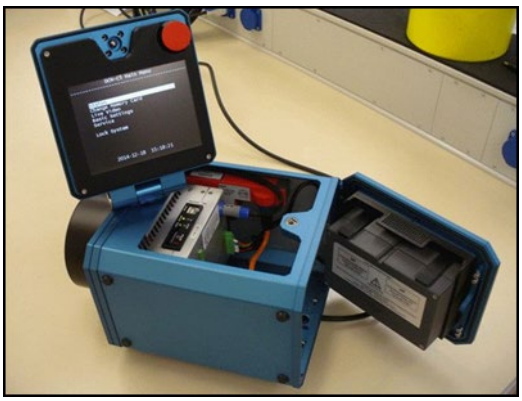

Figure 8: The (open) XCAM with DCD (on top), battery (on open rear door) and AC power supply (red part next to DCM C5) (courtesy: EURATOM, Luxembourg).

Installed Single or Small Number of Camera System for Difficult to Access Locations

DSOS. The Digital Single Camera Optical Surveillance System (Figure 9) is based on DCM 14 technology and is designed for applications where the camera must be placed in a difficult to access location. DSOS consists of a DCM 14 based digital camera connected to a recording unit by a special composite cable. The recording unit, which is **also based on DCM** 14 technology, allows an inspector to service the system at a more convenient and safe location using procedures similar to those used when servicing an ALIS. For practicalities of upgrade the housing from the MIVS could be reused.

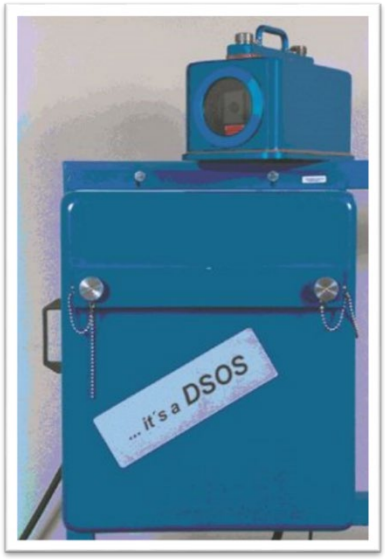

Figure 9: DSOS: Digital Single Camera Optical Surveillance System (courtesy: IAEA, Vienna).

XSOS: The XSOS was developed to replace the DSOS and create small (up to 4 cameras) surveillance systems. It fits in the same (MIVS) housing, uses the same cables and allows a speedy upgrade. The core component is a DCI (Digital Camera Interface – able to concentrate data and redundantly recording images from up to 32 DCM C5 or 14) plugged in the DCR-1 (Digital Camera Recorder 1). Due to the limited power supply (24V/5A) and the limited space for cable connections it is used only for maximum of 4 cameras (Figure 10).

Figure 10: XSOS with power supplies (on top) and DCR-1 (below), and place for a VPN router (courtesy: EURATOM, Luxembourg).

Installed Multi-Camera Systems

DMOS. The Digital Multi-Camera Optical Surveillance (Figure 11) is designed for unattended and remote monitoring applications. DMOS is used for applications requiring between 6 and 16 cameras connected to a central recording and communications console. DMOS is based on DCM 14 technology and each camera is interrogated by a server computer. Images and data from each camera are initially stored on a RAID array prior to final storage on a removable digital linear tape (DLT) or external hard disk (EHD). It may also be used for the direct interrogation of VACOSS seals.

Figure 11: DMOS (right).

SDIS. The Server-based Digital Surveillance System (Figure 12) was initially developed for remote monitoring applications and to reduce cost and complexity of a DMOS. Its primary function is the collection of images and data from up to 6 DCM 14 surveillance cameras. It may also be used for the direct interrogation of VACOSS seals. The SDIS server calls the images from the connected cameras, sorts and compresses these and other data on the redundant EHDs. It can transfer images and data to headquarter offices via telephone line (PSTN), ISDN, ADSL, frame relay or satellite link. An uninterrupted power supply unit is an integral part of SDIS and has been designed to keep the system in full operation for about 48 hours without an external mains power supply. 3 types of SDIS are available: the SDIS v1 in the blue container (Figure 12), the SDIS v2 (both IAEA) in a half high 19" cupboard with DC UPS and SDIS v3 (EURATOM) in a full high 19" cabinet with an AC UPS.

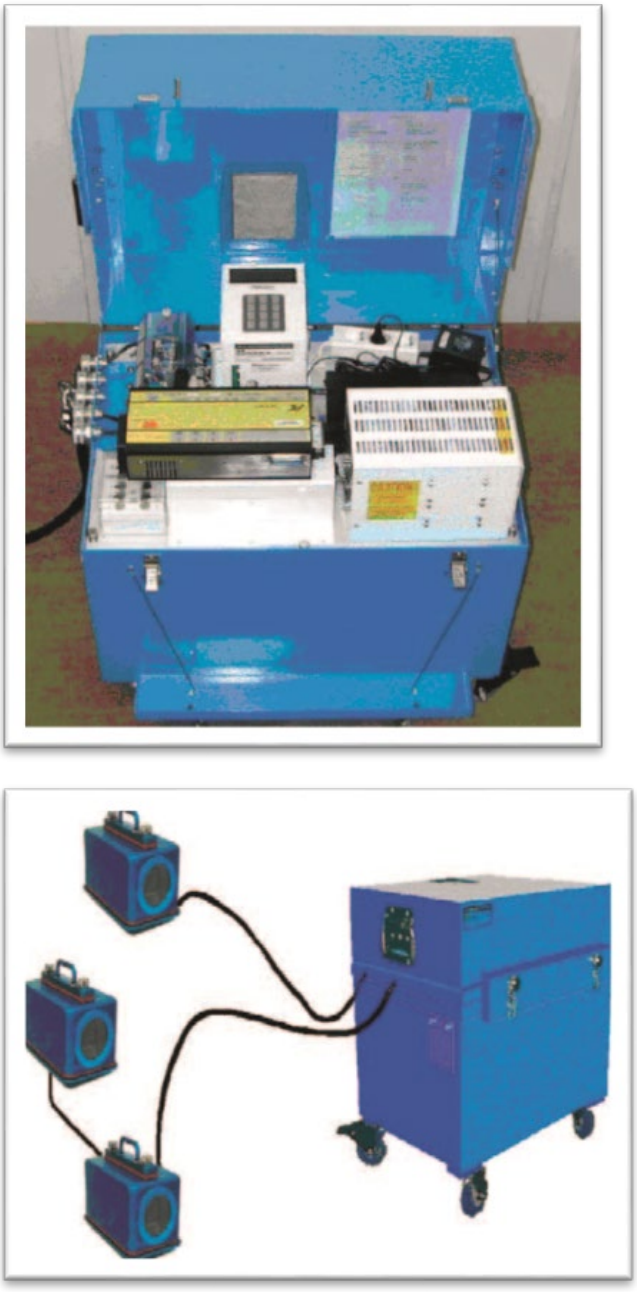

Figure 12: SDIS (top left) and (open) SDIS server (bottom left) (courtesy: IAEA, Vienna).

XMOS: The XMOS was originally developed as the replacement for the DMOS by the US SP (Figure 13). But the prototype was too heavy and costly. A 12-channel system fills a full height 19" cabinet and cost more than 120 000 $ (without cameras), because each camera has its own DCI, all together a common server with 2 separate EHD and each component has its own UPS (uninterrupted power supply). Under EURATOM request the system was redesigned by the German developer.
The system consists of up to 32 DCM C5, connected via Twisted Pair (TP), Ethernet or Fibre Optic (FO) cable to the XMOS 19" cabinet (all different housing and cables from SDIS or DMOS can be reused) in which one or several B8 19"racks with a display DCID, a DCI and one or 2 DCS (Dual Comport Server, a DCI extension to 2 high speed RS485 buses) exists, powered by an XPCU (NGSS Power and Control Unit, 2x 24V/20A power supply, up to 40 electronic fuses and a PLC to remotely check the status and control the fuses). The whole system can be set up and checked with a PC connected directly or remote to the internal IP network.

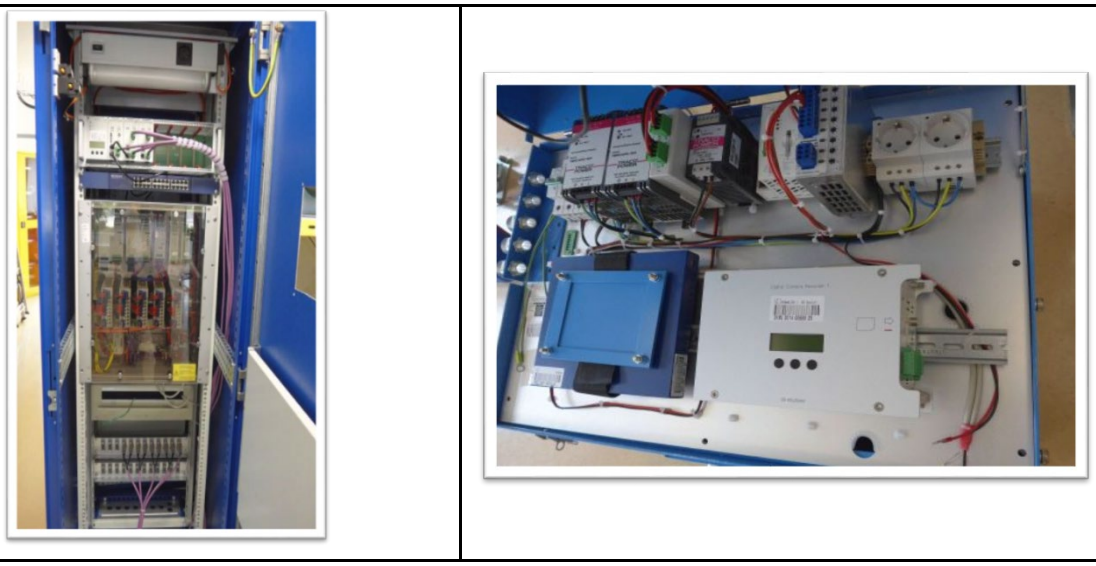

Figure 13: XMOS (top right, on top the B8 rack, in the middle the XPCU) and XDIS (below, as replacement of SDIS v1) (courtesy: IAEA, Vienna).

Surveillance Review Software

Surveillance continues to play an important role in safeguards. There has been a steady increase in the number of camera units deployed in safeguarded facilities (more than 600 cameras in the EU). Equipment has been developed to provide an increasingly sophisticated review capability for the surveillance data. E.g. EURATOM has to review about a half million images per day! That amount cannot be handled manually.

GARS. The Gemini (later General) Advanced Review Station software (Figure 14) was developed to run on a personal computer with the appropriate media drives to review the recorded images from Gemini, ALIP, ALIS, DSOS, DMOS and SDIS. The basic GARS version provides a flexible and user friendly inspector interface (similar to popular commercial media players) for the review of images and data from flashcards, Jaz-type disks, removable hard drives, CD-ROMS and DLTs. GARS also has advanced features that can be used to reduce an inspector's review effort. Those features include image and data authentication verification, image and data decryption, scene change detection of recorded images, digital image enhancement and multiple camera display options.

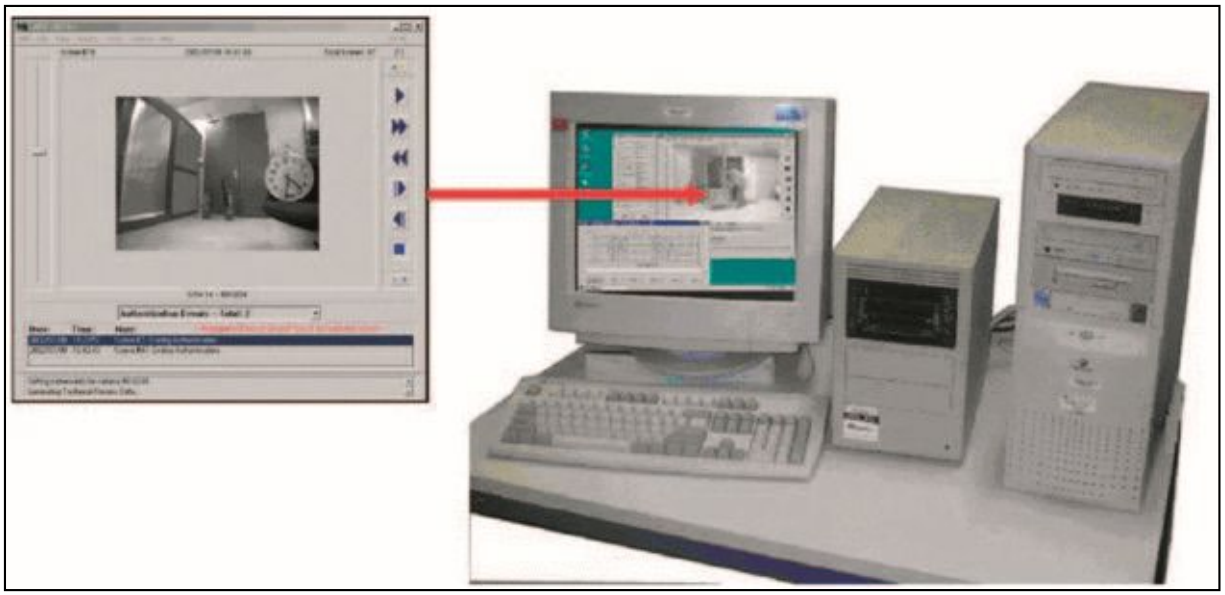

Figure 14: GARS software (courtesy: IAEA, Vienna).

NGSR Next Generation Surveillance Review

This review software was developed in 2019/20 as a replacement for the GARS to review almost automatically the images from several cameras of DIS and NGSS systems. The software is running on a normal (modern) PC under Win10 OS and can be used as a stand-alone tool or integrated in the Integrated Review and Analysis Package (iRAP) to review complex systems with neutron or gamma radiation data, industrial sensor (like bar code or eddy current readers) combined with cameras. This user friendly tool supports different kinds of motion detection and image triggering filters and allow a safeguards report generation with a minimum of manual inputs.

3.2 Seals

Seals, sometimes referred to as tamper indicating devices, are used to secure materials, documents or any other important items in a tamper-proof containment. The purpose of seals is to provide evidence of any unauthorized attempt to gain access to the secured material. The seals also provide a means of uniquely identifying the secured containers. It must, however, be pointed out that the seals do not provide any kind of physical protection, nor were they designed to provide such protection.

Passive Sealing Systems

Passive sealing systems do not require an energy source while the seal remains in place, although in some cases a powered reader is required for seal interrogation. Some of these seals are examined in situ, and some are returned to inspectorate's headquarters for examination. Passive sealing systems represent by far the most common form of safeguards seal.

Metal Cap Seal

The Metal Cap Seal is extensively used for sealing material containers, material cabinets and safeguards equipment (Figure 15). The seal has 2 metallic parts which, when engaged, cannot be separated without leaving evidence due to damage. A dedicated wire (metal or plastic composite) is used as a sealing wire and a knot is tied inside the seal body to close the loop. With the knot inside the seal, the loop cannot be opened without cutting the wire. The main advantages of the seal are its low unit cost, simplicity, physical robustness, and its small size and weight. Attachment and detachment efficiency is important to limit the radiation exposure of the inspector.

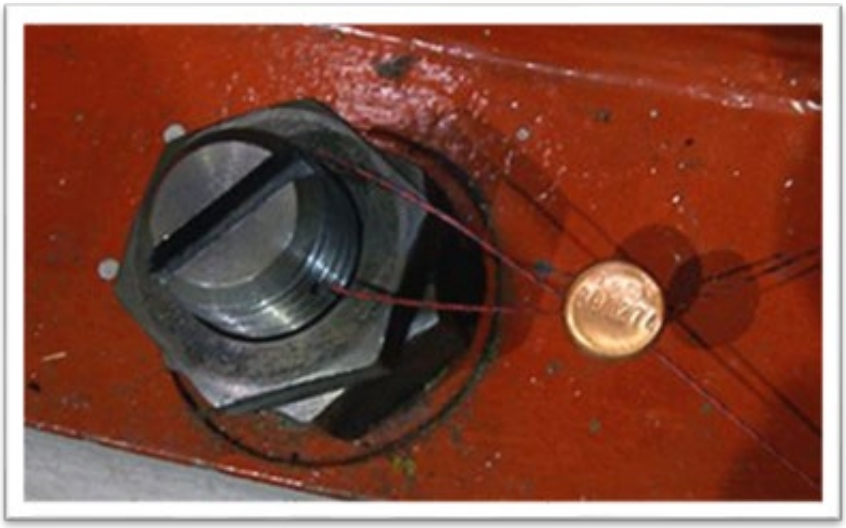

Figure 15: Metal cap seal (courtesy: IAEA, Vienna).

The main disadvantages are that the seal does not monitor the state of the wire, and that seal verification must be performed at the headquarters, which delays the verification conclusion and is time- and resource-consuming. In order to be verified, the seal is detached in the field by cutting its wire and brought to inspectorate's headquarters. Unique identification of each seal is obtained by implementing random features on the inside surface of the metal cap and by comparing the images before installation and after removal (Figure 16).

Figure 16: Comparison of metal cap seal images for seal validation (courtesy: IAEA, Vienna).

In EURATOM and IAEA HQ dedicated equipment is available to partially automate and support the verification process by technicians.

Field Verifiable Passive Seal (FVPS)

After forty years of using the metal cap seal, the IAEA has issued a new development in 2020 to improve the current passive sealing system. The agency aimed to enhance this tool by allowing for example in-situ

verification and tamper indication in the field. As a result, the in Field Verifiable Passive Seal (FVPS) system has been developed and approved for safeguards use (Figure 17).

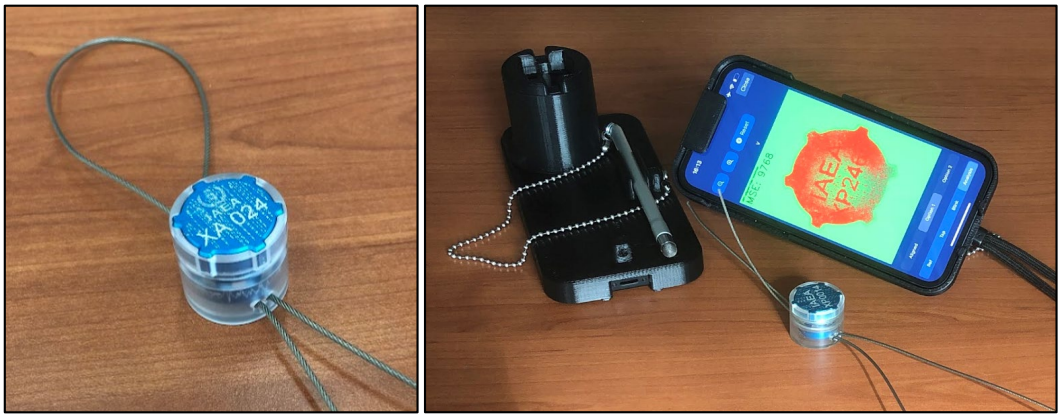

Figure 17: Left: Field Verifiable Passive Seal (FVPS) & Right: FVPS Verifier (courtesy: IAEA, Vienna).

Technical features of the FVPS:

- Polycarbonate cup, easy to manufacture.
- Aluminium plug with star-lock washer to secure closing.
- New, 7x19 wire is thinner and more flexible than current stainless-steel wire used for metal cap seals.
- No tools needed to close the seal– only hands are needed.
- Laser etching for serial number.
- Incorporated swirls, bubbles and flow patterns are unique for every seal.
- Rugged against UV exposure, salt corrosion, galvanic corrosion, temperature, gamma and neutron radiation.

The IAEA developed verification algorithms to perform the verification in the field. For this purpose, the reference image of the seal is captured at time of its application. During the infield verification the image taken during inspection is then compared to the reference image.

Adhesive Seal

The improved adhesive seal is made of a special material which cannot be removed without leaving evidence of seal damage (Figure 18), therefore a re-attachment of the seal is not possible. As for all adhesive seals, the seal is intended only for temporary applications (24 hours or less). Its main advantages include the ease of use, low unit price, and low-cost operations, maintenance, and logistics. The seal is intended for use in a wire wrap application and on different surfaces (such as metal, plastic) and is available in two sizes. The Agency uses about 12,000 of these seals per year, EURATOM about 1,000.

Figure 18: Adhesive Seal (courtesy: IAEA, Vienna).

COBRA/FBOS Seal

The COBRA/FBOS seal consists of a plastic body and a fibre-optic loop (Figure 19). The seal wire is a multi-strand plastic fibre-optic loop with its ends enclosed in the seal in such a way that a unique random pattern of fibres is formed.

Figure 19: COBRA/FBOS seal (courtesy: IAEA, Vienna).

This can be verified by shining light into the ends of the loop and observing the pattern of the fibre ends by means of digital image recording. Immediately after the seal is installed, a reference image of the seal signature pattern is taken. Upon subsequent inspections, follow-up images are taken. The COBRA/FBOS seal reader stores digital images and is able to aid in comparison of the patterns. This procedure enables an inspector to verify the seal identity and integrity in situ without removing the seal, hence without breaking the safeguards containment. The seal is small, light and inexpensive. It allows for multiple subsequent verifications on site, a wide ambient temperature range, and no electrical power is required. It can stay attached for long periods of time, in some cases, like on spent fuel casks, for years.

Ultrasonic Sealing Bolt (USSB)

The ultrasonic sealing bolt (USSB) has been designed by the Joint Research Centre of the European Commission in Ispra, initially for securing underwater storage of spent fuel assemblies. Identity is made of cavities drilled in stainless steel disks brazed together in a random manner (Figure 20). These flaws can be read with a dedicated ultrasonic reading head, underwater. The reading gives a unique and non-reproducible identity, different for each single seal. The inspectorates have the database of the various seals and their status. When on site, they recall the seal number and verify that the identity reading is still the same as the reference reading. A special rod connecting inner and external parts of the bolt will break when removed or tampered. This breakage is read as well with the same reading head, warning the inspector that the seal has

been broken or opened. This design is particularly adapted to harsh environment where other technology is not applicable, underwater and, in high radiation environment. They have been in use for more than 20 years, in La Hague (France) and in CANDU reactor storage ponds (Cernavoda – Romania & Karachi - Pakistan) /9/.

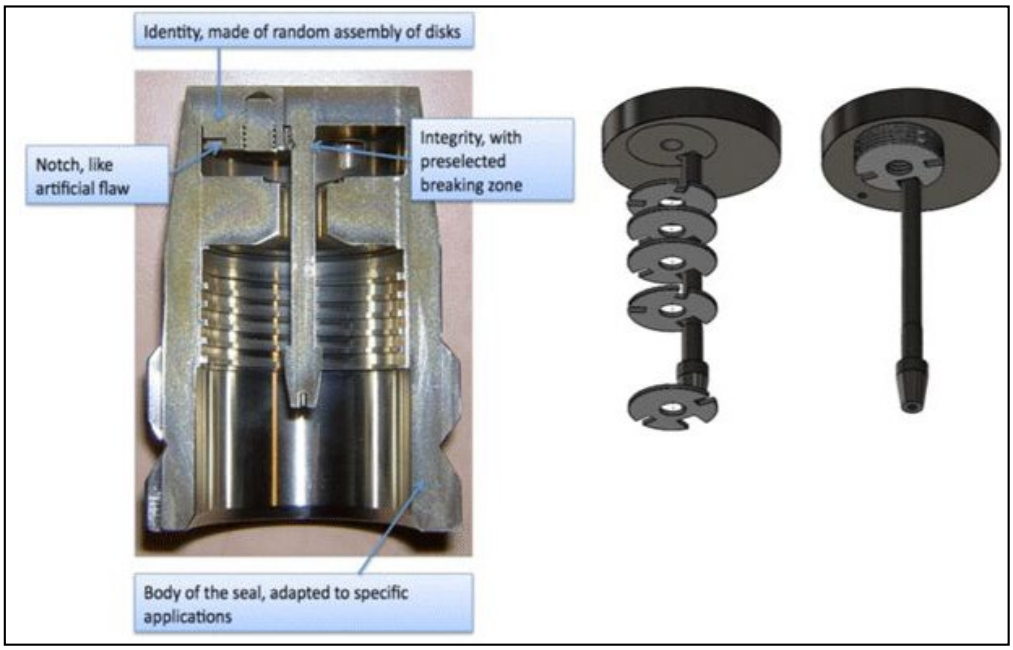

Figure 20: Example of an ultrasonic sealing bolt used for CANDU spent fuel ponds, showing ultrasonic identity and integrity /9/.

Active Sealing Systems

Active sealing systems require power for the seal to operate. This is usually supplied by a long-life on-board battery. An active seal continuously monitors a fibre-optic sealing cable and stores any events, like component status, attack attempts, openings, closings and interrogation, in a secure internal memory. Active seals usually can be supplied with power by a cable which also allows for remote interrogation from headquarters via remote data transmission. Some active seals allow for a wireless communication with a reader. Data security is achieved with encryption and corresponding crypto-keys. Older systems use symmetric encryption protocols, while newest generation of active seals currently under development uses asymmetric encryption, which provides better security and significantly simplifies operational logistics.

Active seals are more complex than passive ones and require sophisticated protection against various attacks/tampering attempts both on the electronics as well as the seal cable. The electronic components also need to withstand significant radiation fields present in some areas of application. This makes active electronic seals more expensive. Nevertheless, they are indispensable for safeguards, providing capabilities not achievable by passive seals (remote verification, communication with other safeguards components like surveillance cameras). Use of active seals has allowed the inspectorates to introduce novel safeguards approaches, like sealing-by-operator, where sealing of particular items can be securely performed by nuclear operators under remote supervision of inspectors, without compromising safeguards quality.

Seal interrogation on-site is done, like in a case of a COBRA/FBOS seal, with a hand-held reader. In fact, a universal seal reader is being developed by an EC Joint Research Centre in cooperation with the IAEA that will allow for interrogation of all joint use sealing systems by one device, hence greatly simplifying operational logistics.

Electronic Sealing System

The inspectors started to use electronic sealing on a routine basis in the early 1990's. The sealing method is based on the measurement of light transmitted through a fibre optical cable that is connected to a secure box with electronic circuitry.

Electronic Optical Sealing System (EOSS)

At the moment, the most commonly used active seal is the electronic optical sealing system EOSS (see Figure 21) which started to be implemented for inspection use in 2006. The sealing function is realised by using a fibre-optic cable (FOC). Fibre-optic cables are generally more difficult to tap or bypass and to repair than electrical wires.

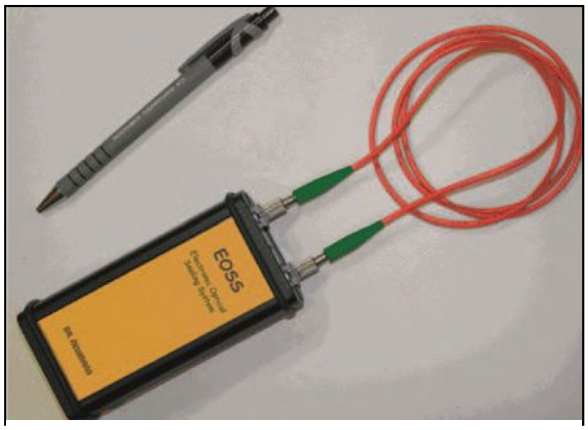

Figure 21: Electronic Optical Sealing System (EOSS) (courtesy: Dr. Neumann Consultants, Grafschaft).

The seal has a light source and a light sensor with the light being transmitted through an external FOC. The FOC is designed for multiple connection and disconnection. It can be manually "opened", i.e., disconnected, and "closed", i.e., connected, without using any tool. Every opening and closing is registered by the internal micro-controller with annotation of date and time. The open/closed status of the FOC is monitored by transmitting and receiving short light pulses at certain time intervals. When the FOC is closed, every light pulse is immediately detected by the receiver. If no signal is detected, then the FOC is considered to have been opened. Moreover, the seal checks for the tamper-indicating event of light being received with the optical transmitter being switched off.

EOSS uses a single-mode cable that has to be operated with laser light. In contrast, the multi-mode technology uses considerably larger fibre core diameters as well as normal light, typically from light emitting diodes. The higher requirements regarding precision, make single-mode systems more difficult to tamper with.

The EOSS housing consists of two compartments. Whereas the inner part contains all security-sensitive components, the outer part houses the batteries as well as the electrical and fibre-optical connectors, in order to facilitate repair.

The battery pack consists of two lithium AA-cells for redundancy and dedicated electronics for monitoring the battery lifetime. The lithium technology provides a high energy capacity as well as a wide temperature range from –20 to +85°C. A single battery will power the seal for a few years.

At very low temperatures, certain memory cells tend to keep their information for a long time even without power supply. Theoretically, this would allow to retrieve the authentication keys by deep freezing the seal and short cutting the battery. Therefore, the temperature is monitored and, at very low values, the keys are erased.

The EOSS registers different categories of events. The Seal Log contains openings and closings of the fibre-optic cable. The User Log contains activities like user log on/off and key-set generation. Moreover, the User Log registers potential or real tamper attacks (e.g., denied requests from the network). The third part of the log contains State-of-Health information (e.g., battery usage, min. and max. temperature).

Data authentication implemented in the seal uses the Triple Data Encryption Standard (TDES).

The EOSS seal has a RS-485 interface. The hardware allows cable lengths of up to 1,000 m. Up to 32 seals can be connected to one twisted pair cable (party-line). The seal reader is a standard notebook or personal computer. A compact size RS-485/RS-232 converter is available to connect the party-line to the PC's serial port.

Ultrasonic Optical Sealing Bolt (UOSB)

A dedicated version of the Ultrasonic Sealing Bolt, called Ultrasonic Optical Sealing Bolt (UOSB) has been recently designed to provide a reliable sealing blot for CASTOR and CONSTOR dry storage containers used in Ignalina – Lithuania (Figure 22). The ultrasonic principle is the same, the identity/integrity is read using water as a coupling medium, inserted between the reading head and the bolt head. The main difference is an optical fiber connected to a Cobra seal or an EOSS seal which is passed through the integrity rod by the inspector after the installation of the bolt. The ultrasonic integrity and the fiber are both cut when the seal is removed and/or tampered with. Having a reliable sealing bolt on the top of the casks, the inspectors can rely on the Cobra and/or the EOSS readings at the floor level or even in real time if the EOSS has Remote Data Transmission capabilities /10/.

Figure 22: Left: Four different types of UOSBs (Castor, Constor, EOSS & Cobra), center: reading head over the seal, right: UOSB to be bolted on a Constor casks in Ignalina /10/.

3.3 Containment Systems

In the process of selecting a safeguards approach, all aspects of containment systems must be considered. The containment is as important as the seal that protects it. The severity of the consequences of potential loss of containment integrity should drive the choice of the sealing method and its sophistication. However, even if the perfect seal could be developed and deployed, CoK cannot be maintained without also knowing that the containment is intact. Currently, this is left to the inspector to visually check for tampering. However, there could be more effective methods to detect possible tampering. Current containment systems include the following.

Instrument Cabinets

Instrument cabinets house radiation detectors, computer network, data storage and video surveillance equipment. The EC and IAEA specifies and owns the instrument cabinets and conduits, so that it has control over design and built-in tamper indicating features. Tamper indication is added to the cabinets in the form of coatings, surface finishes, welds, and seals.

Nuclear Material Storage Containers

Containers are generally specified by the user facilities, not the inspectorates. The problem also lies in the number of different types of containers that have been designed for specific applications. Containment can indicate storage containers, shipping containers, casks, spent fuel ponds, vaults, and many others.

The obvious question that needs to be resolved is how to verify many different types of containers with minimum impact on the inspection process and minimum hampering of plant operation. Periodically, the EC and IAEA re-measures a small randomly selected percentage of material under C/S to add confidence that containment has not been breached and no diversion has taken place.

Conduits

In most cases, data are authenticated and encrypted at the instrument level and a tamper indicating conduit is not necessary. However, in cases where authentication is not possible, secured conduit is used to provide power and data transmission between radiation exposed equipment (sensors and their monitors) that may be located in potentially damaging high-radiation environments. Metal conduit is the only type of conduit used in these applications. Conduits must be physically inspected to verify that tampering has not occurred. A means to effectively inspect the conduit needs to be identified.

3.4 Laser Methods for Containment Verification

In recent years, laser containment verification methods have been developed and applied in various safeguards applications. Lasers can be used as a sealing method for an individual container, as well as for area-monitoring/sealing. Given the increasing number of spent fuel stored in casks around the world, laser monitoring systems are gaining importance in application. In particular, in situations where placing physical seals on items is too prohibitive due to strong radiation fields, area-monitoring becomes a viable alternative.

Laser Mapping for Containment Verification (LMCV)

The Laser Mapping for Containment Veri¬fication (LMCV) has been developed as an alternative for sealing spent fuel containers. For a container which is closed by welding rather than bolts, the weld itself can act as a seal. LMCV is a device that precisely scans parts of the weld and obtains a unique weld signature that is impossible to falsify/reproduce. Any attempt to open the container in the weld vicinity would destroy the weld signature and be detectable by a subsequent verification scan. LMCV is a hand-held instrument that is precisely anchored in the weld verification area; the process of verification takes a couple of minutes (Figure 21 and 22). A version of the LMCV exists that can be operated by site personnel without the presence of an inspector. The scan data is then automatically and securely transmitted within specified timeframe via remote data transmission to inspectorate headquarters.

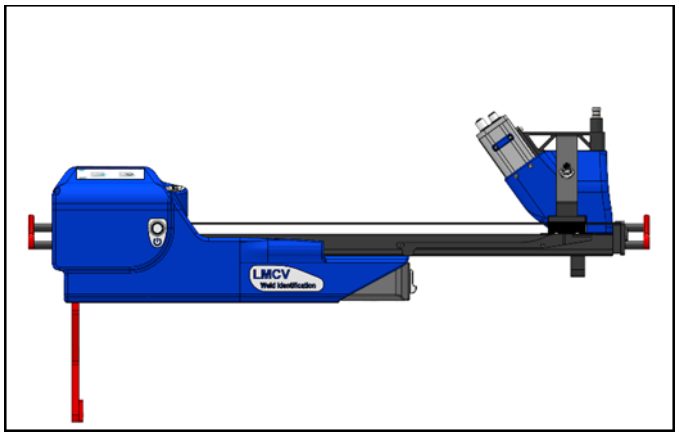

Figure 23: LMCV (courtesy: Joint Research Centre, Ispra).

Figure 24: LMCV scanning weld of spent fuel cask (courtesy: IAEA, Vienna).

Laser Curtain for Containment and Tracking (LCCT)

The Laser Curtain for Containment and Tracking (LCCT) consists of one or more laser scanners mounted on site structure (walls, railings etc.). It is an active system that continuously monitors in real-time a user-specified area of interest, creating a virtual "box" (that can be quite complex in structure) around items to be safeguarded (Figure 25). Any intrusion into the area of interest by an object larger than a specified limit is automatically detected and recorded. It can trigger event alarms and additional safeguards measures like optical surveillance. This system can also be used to track movements of objects within a given area, e.g. movement of spent fuel containers in a facility.

Figure 25: LCCT system combined with NGSS (courtesy: Joint Research Centre, Ispra).

3D Laser Verification System (3DLVS)

The 3D Laser Verification System (3DLVS) is a stand-alone instrument that uses a laser beam to create a highly accurate 3D model of the configuration of items in a facility, which is used to verify the absence of undeclared changes between on-site inspections. For example, it can be used in a storage hall with many containers, or in an enrichment facility that contains a large complex network of containers and pipes. Once a detailed initial reference scan is made, the configuration of the facility is "frozen" and even the minutest changes can be detected upon a subsequent verification scan during a follow-up inspection. 3DLVS can be considered as a passive sealing system, as it does not continuously monitor the area of interest.

4 Research and Development

R&D is a permanent task in the field of C/S with regard to the fast development of hardware and software. As with any protection from unauthorized access, the longer a given measure remains in use, the higher the probability that potential adversaries find and exploit its weaknesses. For that reason, C/S safeguards systems have to be continuously improved and new ones developed. A lot of aspects have to be considered, such as cyber security, which gets more and more important and systems have to be up to date in that regard. Additionally, essential electronic components of existing systems are no longer available due to outdating, electronic devices are only maintainable for a specific amount of time etc...

Furthermore, there is a development of new electronic devices which may also be suitable for safeguards applications e.g. RFID Tags or laser systems as described in 3.4. Another point is the efforts undertaken to rely more on the support and cooperation of the site operator to increase effectiveness and efficiency of safeguards. In particular, there is a need for sealing systems which can be applied and detached by the operator without having to be physically verified by an inspector in between those two events. This is a very difficult objective to achieve without compromising safeguards quality and effectiveness. Efforts are currently underway to improve or replace all existing containment/sealing systems with new ones. In this regard the in Field Verifiable Passive Seal (FVPS) has been developed as a replacement for the metal cap seal. The goal

was to make this basic seal verifiable in situ, while improving its tamper resistance. A new electronic active seal development is close to completion that promises better security with asymmetric encryption. As laser technology continuously improves, the devices offer more capabilities like better resolution, more scanning lines, wider scanning angles etc... All that translates to improved coverage of the area of interest, hence better safeguards security. The ultrasonic sealing bolts are a very robust sealing system, and can be adapted to various applications. In connection with active components and when combined with camera or laser surveillance, they promise to provide a seal that can be installed and perhaps also removed by the plant operator without much supervision of the Inspectorates.

Naturally, due to the importance of nuclear safeguards and the possibly catastrophic consequences if they fail, all newly developed systems must undergo stringent tests and evaluation before approval and implementation to minimize any risks associated with possible failure/compromise. To mitigate such risks, the Inspectorates never rely on a single containment measure, but rather use at least two different technologies in connection with surveillance and other measures, in accordance with defence-in-depth and redundancy principles.

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Note: Previous C/S chapter can be found in the ESARDA C/S archive!

Material Balance Evaluation

A Constitutive Part of the Implementation of the EURATOM Treaty Safeguards Approach in the EU

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Abstract

EURATOM Safeguards are supposed to "make certain, by appropriate supervision, that nuclear materials are not diverted to purposes other than those for which they are intended;" (Art 2 (e) EURATOM Treaty). The implementation of EURATOM safeguards is based on conformity assessment criteria aiming at verifying that, in the territories of the Member States, nuclear materials are not diverted from their intended uses (art. 77 a EURATOM Treaty) and that international obligations are complied with (art. 77 b EURATOM Treaty).

Material Balance Evaluation, or MBE activities, are based on the physical as well as nuclear accountancy verification of the various nuclear facilities in the EU, and deal with the concept of safeguards confidence using both statistically sound methodologies as well as qualitative assessments.

This lecture aims at introducing the basic elements of the EURATOM safeguards approach from an MBE perspective, discussing all the building blocks required for our EURATOM safeguards assessment and related safeguards conclusions. This requires focussing on the key concepts and tools that EURATOM safeguards use to bridge the gap between the political and the technical dimensions. In other words: translating the political objective to ensure that no nuclear material has been diverted, into reasonable assurance, or confidence, in the nuclear safeguards conclusion that such materials have actually not been diverted.

Exploring the MBE concepts, the reader is gradually exposed to the various steps of the EURATOM nuclear safeguards approach including objective performance indicators as well as subjective, expert judgement. These factors are all needed, because "Not everything that counts can be counted, and not everything that can be counted counts." [92]

Keywords: EURATOM; EURATOM Treaty; Nuclear Safeguards; Nuclear Inspections, MBE, MUF.

1. Introduction

This lecture is organised in four main sections. Starting with The EURATOM Legal Framework, the author explores the extraordinary power of the European legal framework in entrusting the Commission to establish a system to verify and rectify the safeguards performance of all nuclear operators in the EU. The EURATOM law is presented top to bottom starting with the founding Treaty and proceeding to related secondary and soft legislation, all the way down to the safeguards implementation provisions.

The EURATOM Safeguards System is then discussed in terms of its basic principles. Space and time divisions, as well as measurements and their inherent technical limitations, are shown to be both the knowledge

[92] Albert Einstein.

providers and the information side-lines separating the statements expressed with certainty from those expressed with a certain confidence.

In a following section, the safeguards verification activities are described in the framework of accountancy, flow, and inventory inspections, complemented by material balance evaluations to tie back together all the safeguards observations and consolidated knowledge.

Finally, a section specifically dedicated to the Material Balance Evaluation Processes outlines the activities inherent to the assessment of the material unaccounted for, or MUF, that in bulk-handling facilities results from accountancy systems that cannot account for measurement uncertainties.

The lecture concludes discussing the processes that take all the conformity assessment activities, carried out by EURATOM at nuclear installations in the territories of the EU Member States, to Nuclear Safeguards Conclusion, drawn for every material balance area, MBA, and each material balance period, MBP.

2 The EURATOM Legal Framework

According to Chapter 7 of the Treaty establishing the European Atomic Energy Community (EAEC) or "EURATOM Treaty" [1], the European Commission has the following core safeguards objectives in the territories of all European Union (EU) Member States [2]:

- Ensure **non-diversion** of nuclear materials to unauthorised channels under Article 77 a[93]: *"The Commission shall satisfy itself that … ores, source materials and special fissile materials are not diverted from their intended uses as declared by the users"*;
- Ensure compliance with **international obligations** with non-EU States and international organisations under Art. 77 b: *"The Commission shall satisfy itself that … safeguarding obligations… under an agreement concluded with a third State or an international organisation are complied with."*

Beyond chapter 7 of the EURATOM Treaty as **primary law** focussing on nuclear safeguards, rights and obligations of the European Commission, EU Member States and nuclear operators are further defined in Commission Regulation (EURATOM) No 302/2005 of 8 February 2005 on the application of EURATOM safeguards (**secondary law**).

Moreover, the European Commission adopted **two recommendations** to provide guidance and to facilitate the implementation of Regulation 302/2005. Although not legally binding, they are practically persuasive "soft law":

Commission Recommendation of 15 December 2005 (2006/40/EURATOM), giving guidance to the nuclear operators on the information to be provided to the European Commission and

Commission Recommendation of 11 February 2009 (2009/120/EURATOM), providing guidance on how to implement a high quality Nuclear Material Accountancy and Control (NMAC) system.

Finally, specific safeguarding provisions complement the legal pyramid of EURATOM safeguards law. These – legally binding – Commission Decisions, adopted on the basis of Article 6 of Regulation 302/2005, define **Particular Safeguard Provisions** (PSP) for individual nuclear installations.

[93] All references to Articles in this text refer to the EURATOM Treaty unless otherwise stated.

To illustrate the power of this European legal framework for an effective implementation of a comprehensive nuclear safeguards verification scheme, it is useful to highlight its four legal dimensions [3]:

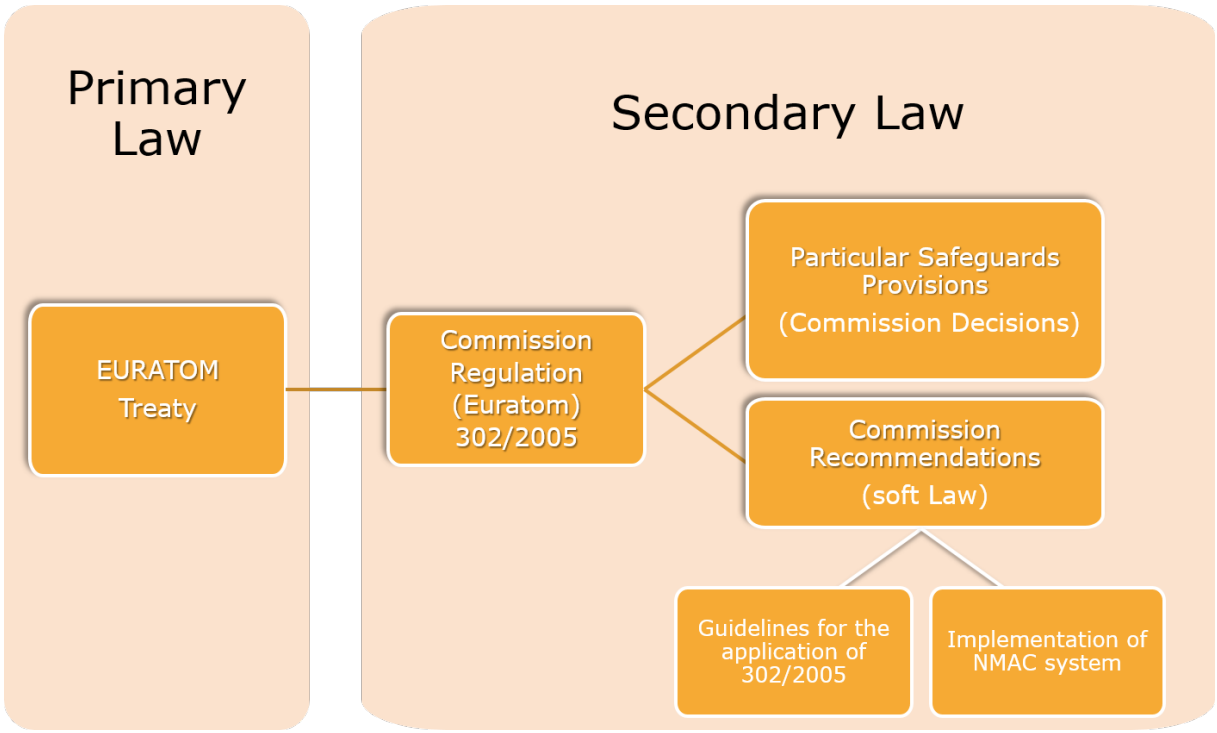


Figure 1: The EURATOM legal framework.

- *Supranational dimension*: In general, the EURATOM Treaty has **primacy** over national law of the EU Member States (Article 106a in conjunction with the Declaration concerning primacy to the Treaty on European Union – TEU - and the Treaty on the Functioning of the European Union - TFEU). Its Article 82 confers upon the Commission **enforcement** rights vis-à-vis the Member States in the case of infringements and imposes on the latter a **duty to cooperate** under Article 192.
- *Supervision dimension*: Under Article 81, the Commission not only sends **inspectors** to the territories of the Member States but may also impose **sanctions** directly onto nuclear operators under Article 83 of the EURATOM Treaty.
- *International dimension*: Based on bilateral EURATOM agreements under Article 77 b, the European Atomic Energy Community has established relations with **third countries**, (e.g. USA, Canada, Australia, etc.) mainly to ensure the frictionless supply of nuclear materials into the EU under the conditions of the Non-Proliferation Treaty context.
- *Cooperation dimension*: Based on multi- or trilateral agreements between the Commission, the **International Atomic Energy Agency** (IAEA) and Member States under Article 77 b, the implementation of verification activities in the EU is coordinated and shared between the two safeguards organisations.

Therefore, EURATOM primary and secondary law provides an efficient set of **instruments (verification, enforcement and sanctions)** to verify and, if need be, to also rectify the safeguards performance of all nuclear operators in the EU [4].

In terms of implementation, EURATOM law stipulates that it is the nuclear **operators** that are the **primary responsible** for nuclear material control in their installations. Nuclear material flows, inventories, and installation characteristics must be recorded, documented and reported to the Commission. Additionally, all nuclear operators must implement a Nuclear Material Accounting and Control (NMAC) system that is credible, effective and based on measurements conforming to the latest international standards.

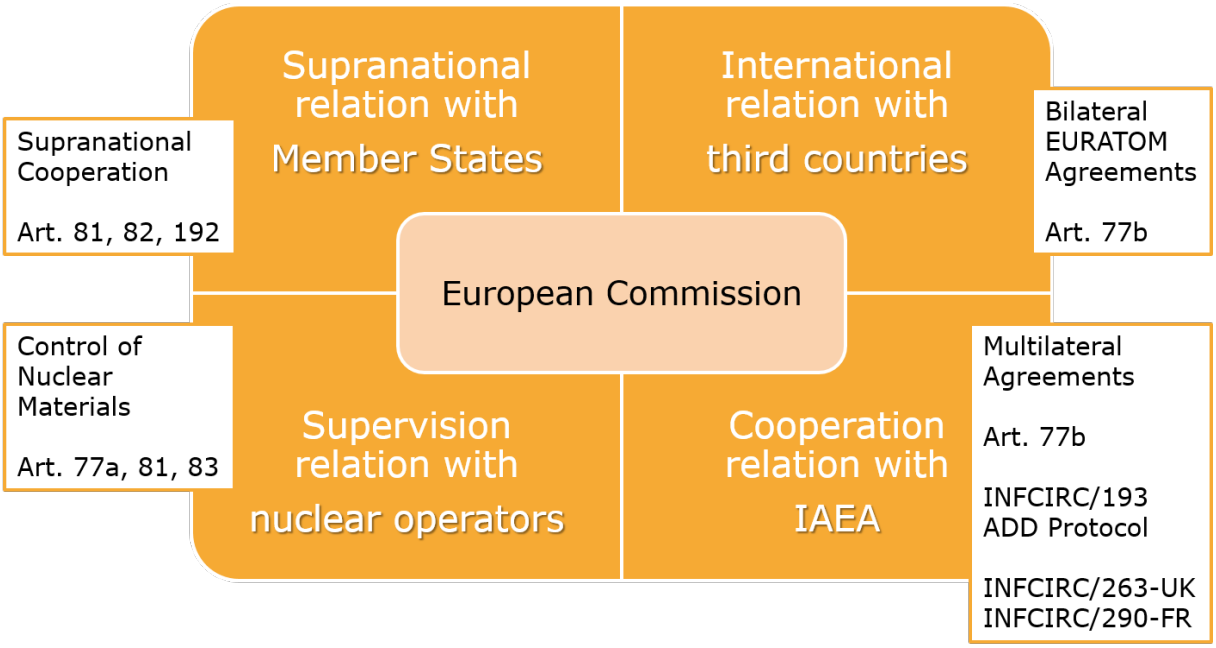


Figure 2: The EURATOM four legal dimensions.

The NMAC system therefore has to provide an accurate and timely account of location and quantity of all nuclear materials under safeguards control to the Commission. It also needs to be able to detect any real or apparent losses in due time. This requires performing Material Balance Tests to ensure that legitimate measurement uncertainties can explain any Material Unaccounted For (MUF) when taking a physical inventory.

The Commission plays the role of a **supervising body**, responsible to seek assurance that all provision of the EURATOM Treaty and its derived law are complied with. This may be achieved

- through independent verifications along with audits of the NMAC systems,
- by formulating recommendations and opinions resulting from the inspection activities,
- through directive recommendations addressed to a Member State under Article 83 (3),
- by corrective measures in the form of direct legal actions (enforcement and sanctions) against the Member State and the nuclear operator in the case of an established infringement under Articles 82 and 83.

The Commission's current approach for implementing its safeguards system was established in 2007, as set out in the 2007 Commission Staff Working Document on the implementation of EURATOM Treaty Safeguards. In 2021 the Commission updated this approach in order to better reflect recent developments in the field of safeguards such as the increasing task of decommissioning of individual nuclear installations, the safeguards treatment of deep geological repositories and the handling of the increasing number of small holders of nuclear materials. This approach is reflected in the current Implementation of the EURATOM Treaty Safeguards, staff working document.

3 The EURATOM Safeguards System

The EURATOM legal framework requires the Commission to implement a system for supervising the declared use of nuclear materials in the territories of the Member States. Such system, designed to assure the operator's compliance with legal provisions, requires a combination of

- Auditing methodologies, as elements of supervision of NMAC systems, and
- Inspection methodologies, as physical verifications using nuclear measurements and verification of the operators' declarations both at headquarters and on-site.

Therefore, the Commission first ensures that the operator's NMAC system is fit for purpose, and then makes use of it to verify that the operator does not physically divert nuclear materials from their intended uses. Additionally, the Commission ensures the absence of deliberate alterations in the operator's accounts to conceal diversion, clerical errors or incompetence, with the intention to deter, dissuade, and ultimately prevent diversions from taking place.

The EURATOM verification activities and the inspection effort are designed against the risks of diversion by the nuclear operators, which in turn is directly responsible of the risk of thefts by unauthorised parties. Therefore, the inspection frequencies are established on the basis of objective safeguards data[94], as well as on expert observations and professional judgement.

The Commission makes use of independent data when available, but makes every effort to maximise the trust and use of the operator's data, measurements and samples to draw independent conclusions.

3.1 Measurement Systems

Measurements play the role of foundations of a safeguards system based on physical verifications. As evident through the course of this lecture, the limitations of any measurement system represent one of the most challenging aspect in nuclear safeguards. Through measurements, and measurement uncertainties, EURATOM safeguards is able to address the fascinating dilemma of how to bridge across the political expectation of absolute assurance and the technical reality of measurable confidence that no diversion has taken place in any European nuclear installation.

The operator measurement system must therefore be fit for purpose, in line with latest international standards, able to provide measurement results in line with the most recent International Target Values[95], reliable estimation of measurement uncertainties, and ensure metrological traceability of the measurement results. The evaluation of such compliance criteria requires

- A quality control system based on independent measurements;
- That calibration certificates are examined and calibrations are witnessed;
- The verification of measurement equipment;
- Audit of the operators' measurement systems;
- The performance of a Material Balance Test.

[94] E.g. safeguards significance of nuclear material quantities and categories (P, HEU, LEU, N, D, T), IAEA inspection impact in NNWS and selected NWS MBAs.

[95] The effectiveness of quantitative safeguards verification activities depends upon the quality of facility operator's declarations and the inspector's verification measurements. The *International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials* are the international standard for the quality of measurement, and serve as global limiting criteria in material balance. The review of ITV 2010 is foreseen to be completed in 2020, as highlighted in the contribution no 365 to the IAEA Symposium of International Safeguards 2018.

While this lecture refers to the complete set of EURATOM conformity assessment activities, the main focus will remain on the elements relevant to establish, with a sufficient level of confidence, that material balances established and declared by nuclear operators are correct. With this concept in mind, and with emphasis on limitations as often is the case in scientific approaches, we are now ready to explore the frameworks defined to build the EURATOM safeguards confidence.

3.2 MBA and MBP Framework

Nuclear operators are subject to reporting obligations that require maintaining accurate balances relative to transfer, holding, and transformation of nuclear materials. The framework of such obligations requires space divisions, the Material Balance Areas - MBA, and the discretisation of time into periods between two successive physical inventory takings, the Material Balance Periods - MBP. Each operator of a facility under EURATOM safeguards must measure, account for, and declare all the nuclear material moves that occurred in and out of each MBA of the facility during the course of an MBP.

The discretisation of space and time constitutes necessary boundary conditions to the verification activities and provides a framework to the relative safeguards conclusion. On the other hand, such structure presents limitations such as yielding different conclusions when evaluating a pair of MBAs and/or MBPs jointly rather than individually.

Additionally, nuclear operator must produce accountancy declarations, based on operating records that are originated by measurement and nuclear materials tracking processes. Since the result of a measurement process requires the statement of a result and of a measurement uncertainty, the regulatory requirement to track transfer, holding, and transformation of nuclear material poses the additional challenge to take account of the measurement uncertainties.

Next section clarifies the terms of this challenge, focussing on measurement uncertainties and their role in safeguards.

3.3 Financial vs. Nuclear Material Accounts

Investigating the analogies and differences between these two types of ledgers will provide the elements necessary to appreciate that measurement uncertainty plays a central role in safeguards declarations and verifications.

Let us compare the principles of bank account, or financial account, to those of an MBA, or nuclear material account. A bank account holder would expect to receive statements showing the opening and closing balances related by all the financial transactions occurred in a given period of time. The same way, the accounts of an MBA need to relate the beginning and the ending of book inventory via all the nuclear material transactions occurred over an MBP.

In analogy with financial transactions in and out of a bank account, nuclear materials are shipped to and from an MBA. Money can be quantified without uncertainty, such as nuclear materials that are handled in the form of items. Nevertheless, in bulk handling facilities, nuclear materials are managed in loose form and are subject to transformations. Therefore, while money and nuclear material items can be counted and accounted for, nuclear materials in loose form are measured, affected by uncertainty, and accounted for.

Stretching the analogy, one may be tempted to assimilate interest and charges affecting financial accounts to positive and negative MUF values relative to nuclear material accounts. This would not be correct, though, as interests and charges are univocally determined and can be verified with the help of a bank account

statement. On the contrary, the MUF is of random nature and unknown origin, and it may well be acceptable if justified by legitimate measurement uncertainties, as discussed in section 3.4.

The analogy definitely breaks when considering transfers across accounts. In fact, one would expect declared transfers be mirrored exactly in the sender and receiver account statements. Once again, this would only be the case for accountancy systems such as those of financial accounts or item handling nuclear facilities, because counting processes are not affected by uncertainty. Transfers across bulk handling facilities require measurements to be performed by both the shipper and the receiver[96], resulting in two pairs of measurement results and measurement uncertainties. Since shipper and receiver may be independent facilities located in different countries, these four parameters are relative to two *independent* measurement instruments and procedures. Therefore, the MBA statements are not expected to mirror each other exactly, but rather to report consistent declarations. This, in turns, must be verified through metrological traceability of the shipper' and receiver' results, as discussed in section 5.3. Additionally, unlike financial accounts, nuclear material accounts are subject to physical verifications to establish, for each MBP, that the amount of material present in the MBA corresponds to that declared by the operator as discussed in section 4.2.

In conclusion, the statement of *equality*, which is valid between numbers of items that can be counted, is mirrored by a statement of *consistency*, which is valid between amounts of nuclear material bulks that cannot be counted, but rather measured and subject to physical verifications.

3.4 MUF Origin

As discussed above, despite the absence of counting uncertainty, item-handling facilities can be affected by imbalances due to clerical errors, hidden stocks, uncontrolled losses, or diversion of material. Such anomalies can be addressed by quality management systems, audit, and inspection activities designed to address specific issues. In bulk-handling facilities, though, imbalances can also be due to legitimate measurement uncertainties.

In order to clarify the underlining principles of legitimate imbalances, we observe that during an MBP, operators declare all the nuclear material transactions in (receipts) and out (shipments) of the MBA. In order to account for a transaction, the operator performs a measurement, resulting in a statement of the results and of the measurement uncertainty, expressed as $M \pm \delta$. According to the EURATOM regulatory framework, the accountancy entry A must only reflect the measurement result (i.e. $A = M$), and does not require a statement of the measurement uncertainty in the ledger.

Let us now assume that during an MBP the operator performs N transfers from/to the same container, accounted for as $A_1, A_2, \ldots, A_N$, and relative to the amounts of material measured to have masses $M_1 \pm \delta_1$, $M_2 \pm \delta_2$, …, $M_n \pm \delta_n$. At the end of the MBP, the book inventory, or Balance Accountancy (BA), would only be resulting from the sum of book entries, such that

$$A_1+A_2 \ldots+A_N = M_1+M_2 \ldots+M_N$$

On the other hand, the physical inventory, or Physical Ending (PE) would be the result of a new measurement process, say the measurement of the total mass of nuclear material in the container,

$$M_{TOT} = M_{1+2+\ldots+N} \pm \delta_{TOT}$$

[96] Exceptions: Facilities not in a position to measure the received materials may accept and mirror the values declared by the shipper; accountancy input of reprocessing plants imply shipper's declarations originated by computer model estimations based on fuel irradiation history, rather than on measurements.

Although the uncertainty propagation process is beyond the scope of this lecture, it is important to note that δ_{TOT} will not be equal to the mere sum of the uncertainties $\delta_1 + \delta_2 \ldots + \delta_n$ relative to the individual transactions, but rather to the overall MBP uncertainty calculated, propagating according to the GUM [5], the uncertainties relative to each individual measurement process.

In conclusion, since each move is assessed with an associated uncertainty, the measurement of the totals

$$BA = M_1 + M_2 \ldots + M_N$$

is not expected to be equal to the sum of the individual measurements

$$PE = M_{1+2+\ldots+N}$$

Rather, these are expected to be consistent, and their difference is defined as[97]

$$MUF = PE - BA$$

Since $PE = I_f - I_i$, and $BA = R - S$, we can express

$$MUF = I_f + S - R - I_i$$

Assuming that the MUF origin is only due to the absence of measurement uncertainties in the accountancy ledger, it is legitimate to expect that Material Balance Evaluation activities deal with the role of such uncertainties.

In fact, as outlined in section 5.1, the MUF magnitude is only considered acceptable when justified by the legitimate measurement uncertainty, globally defined as δ_{TOT}.

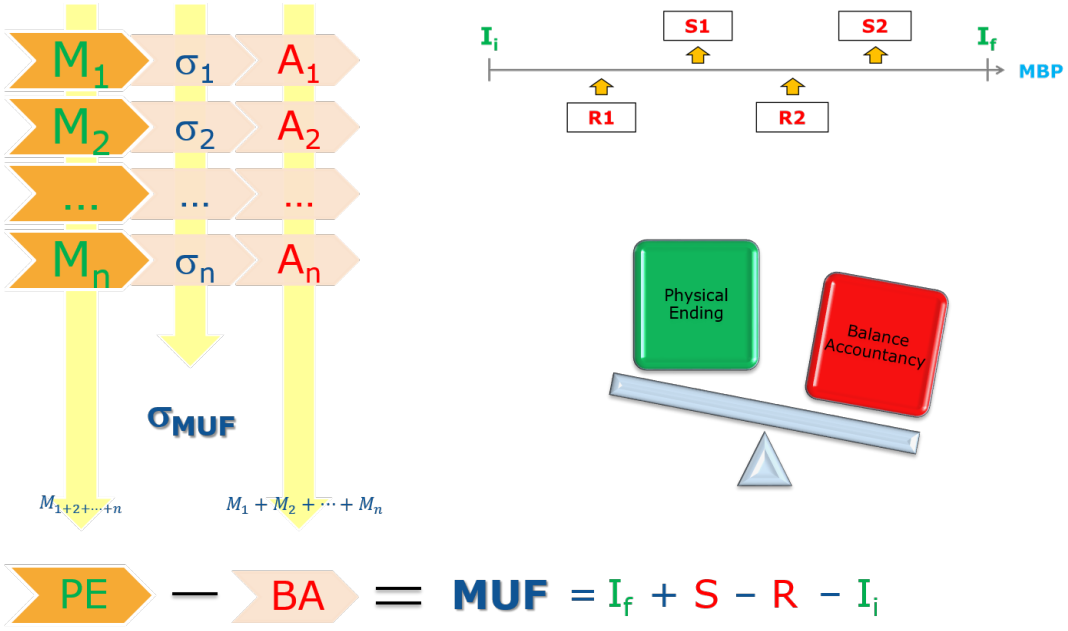


Figure 3: The material unaccounted for, or MUF, is originated by the design of a nuclear accountancy system that does not take account of the measurement uncertainties.

Given the random nature of the MUF, we will express its overall uncertainty in terms of the standard deviation [6] σ_{MUF} from now on.

[97] In IAEA terms, the MUF is of opposite sign, defined as *BA-PE*.

4. Safeguards Verification Activities

Nuclear operators must provide the European Commission with the information and access to nuclear materials required to establish:

- **Compliance**: Legal obligations have been honoured;
- **Performance**: Nuclear materials have been managed with the required level of quality;
- **Non-Diversion**: No evidence of intentional or unintentional removal of nuclear materials from their intended uses.

Therefore, EURATOM safeguards is based on conformity assessment verifications aiming at verifying the completeness, correctness and coherence of the declarations performed by nuclear operators, to ultimately reach safeguards conclusions fact based, and expressed with a statement of confidence relative to the criteria outlined above.

The conformity assessment verifications are classified in three essentially connected, yet complementary processes: First Layer Assessment, Physical Verifications of nuclear material, and Material Balance Evaluation.

4.1 First Layer Assessment

This set of activities is oriented to verify that the nuclear material declarations are transmitted on time to the safeguards services, are reported in the right format, and are fully consistent, coherent, and compliant to Regulation 302/2005. Specifically, these conformity assessment processes address the following requirements:

- The Basic Technical Characteristics (BTC), reporting the general description of the installation, must be representative of the physical reality.
- The accountancy codes employed in the declarations must be the most representative of the physical reality, even in cases that may be subject to ambiguity of interpretation. This entails a very important consultation dimension: individual accountancy issues can be analysed via exchanges between EURATOM and the operator to identify the most appropriate declaration modalities in compliance with the regulation.
- The declarations related to imports and exports of nuclear materials must ensure transaction traceability and comparability of measurement results. These are essential aspects to prove that different measurement results, obtained and reported by shipper and receiver, are consistent within legitimate measurement uncertainties and therefore acceptable. The shipper-receiver difference (SRD) analysis is the object of section 5.3.
- The accountancy declarations must be consistent with declared accounting records, namely the local ledger kept by the operator, and must be supported by operational records.
- The measurement systems implemented by the nuclear operators must have performance and quality that conform to the latest international standards or equal in quality to those as laid down by both Regulation 302/2005 and the verification agreements with the IAEA [7]. Reference standards such as
    - ISO 17025:2005, General requirements for the competence of testing and calibration laboratories, and

- ISO 10012:2003, Measurement management systems - Requirements for measurement processes and measuring equipment,

require that measurement methods are validated, that measurement results are traceable via an unbroken chain of calibrations and related uncertainties, that the measurement process and results are subject to quality control, that personnel competence is ensured, and that environmental conditions are under control.

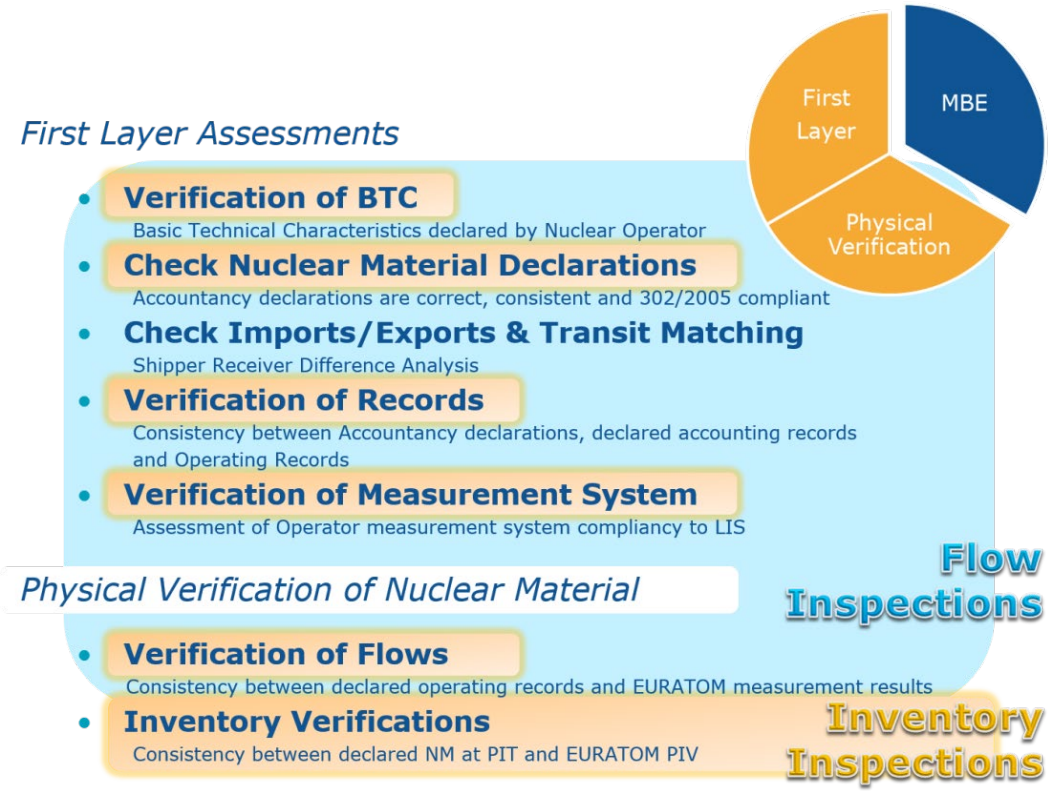


Figure 4: The safeguards verification activities.

First Layer Assessments are routine verification activities, carried out at the EURATOM headquarters to the extent possible, but specifically addressed in the scope of both *flow inspections*, occurring at relatively high frequency, and *inventory inspections*, usually following yearly physical inventory take (PIT) exercises, and therefore mostly devoted to verify the declared inventories via physical inventory verifications (PIV).

4.2 Physical Verifications of Nuclear Material

As mentioned above, the *First Layer Assessment* activities are preparatory to the *Physical Verification of nuclear material*. This group of activities, designed to verify the conformity between the materials declared to be held in an MBA and the physical reality, consist in

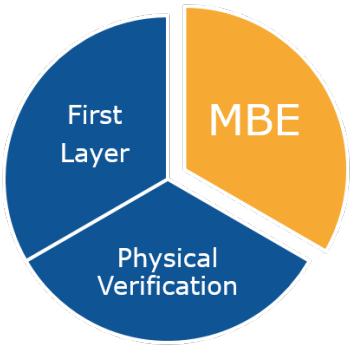
- Verification of flows, namely the consistency between declared material movements with those detected by the EURATOM systems, and
- Physical inventory verifications, consisting in identification and counting of items, qualitative and quantitative tests, and the assessment of results of containment (seals) and surveillance (cameras) activities necessary to verify the declarations related to the physical inventory taking (PIT) exercise, that must be performed and documented by all nuclear material holders.

Physical verifications are crucial activities of the EURATOM safeguards system, are instrumental to consolidate the information provided throughout an MBP and establish a periodical reconciliation with the physical reality.

4.3 Material Balance Evaluation

This group of activities are the essential component to tie *First Layer Assessment* and *Physical Verification of nuclear material* back together. The MBE processes are therefore meant to provide additional assurance on the correctness, completeness and coherence of the nuclear material declarations.

As discussed, both accountancy and physical verification processes are based on measurements and strongly depend on measurement uncertainties. Therefore, it is legitimate to expect that an assessment of the MUF, as declared by nuclear operators, allow the nuclear inspectorate to gain confidence on how nuclear materials have been handled, to ultimately mitigate the risk of drawing erroneous conclusions due to measurement limitations. Nevertheless, the MBE processes range well beyond the MUF evaluation, comprising a set of activities, or sub-processes, described in the dedicated section 5.



4.4 Consultation Frameworks

The effectiveness of the EURATOM safeguards system also relies on communication and consultation frameworks. These are instrumental to consolidate the safeguards practices, harmonise the understanding of the implications of inspection findings, and ultimately establish and promote the safeguards culture.

Once the conformity assessment activities have taken place, the EURATOM services inform nuclear operators about preliminary results of inspection, BTC and inventory verifications, in dedicated closing meetings. However, reaching a nuclear safeguards conclusion requires further actions, and input from several sources, such as measurement results of nuclear material samples by accredited laboratories.

The final results, integrating the outcome of flow and inventory verifications with the results of material balance evaluation, are communicated in writing to the nuclear operator and to the State authority via *letters to the installation*, or LTI. Under the provisions of the Safeguards Agreement, an evaluation of the IAEA's safeguards results is also provided for installations under partnership safeguards approach.

For large sites with several complex installations and multiple MBAs, or when major concerns require to be addressed with specific operators, the Commission may organise meetings involving EURATOM senior management, and annual safeguards performance feedback events involving the facility management and the state authorities. Strengths and weaknesses of the safeguards performance per installation are discussed, and the conclusions of these briefing sessions are fed into the next annual planning. The interactive nature of such events was found to significantly contribute to raise the safeguards awareness of both nuclear operators and state authorities.

As additional exchange frameworks, the EURATOM services hold

- Bilateral meetings to discuss safeguards measures with nuclear operators and outline best safeguards practices;
- Trilateral meetings focussed on the EC-IAEA cooperation in safeguards implementation, evolutions and projects;

- Dedicated meetings to address logistics and communication issues;
- Dedicated meetings and training events tailored on member states representatives.

Finally, the EC and the IAEA continuously promote MBE cooperation involving the nuclear operators and the scientific community in workshops and technical meetings, explore the potential of similar decisional processes, and maximize the use of common information to draw independent safeguards conclusions.

5. Material Balance Evaluation Processes

With an established overview of the EURATOM safeguards verification activities, this lecture can move on to a more detailed description of the MBE processes. In order to factor expert professional judgement in the objective evaluation process, the EURATOM MBE system is characterised by a structure more flexible than that of the *first layer assessment* and *physical verifications*.

The accountancy and inspection activities, aiming at verifying compliance and correctness of operator's declarations, are affected by the characteristic technical limitations of the measurement processes involved. For every MBA, once the BTC, the flows, and the inventory of materials are verified, there remain the need to consolidate the safeguards confidence beyond the space (MBA) and time (MBP) divisions. This is achieved via four sub-processes specifically oriented at evaluating the material balance and reported in the dedicated sections below.

Before entering the process details it is important to note that, in item-handling facilities, measurements of nuclear materials consist in the identification and counting of items as they are transferred in and out of an MBA. Therefore, these measurements result in integer numbers[98], are not affected by uncertainties, and two independent measurements of the same item are expected to yield equal results. Accounting for these materials – unless the ledgers are affected by clerical errors, hidden stocks, or nuclear material gain, loss, or diversion – must result in book values that are equal to the physical stocks at the end of the MBP.

On the other hand, in bulk-handling facilities, where nuclear materials undergo transformations[99], the measurements consist in industrial and analytical assessments of the material quantities transferred or transformed. These are by nature affected by measurement uncertainties, and two independent measurements of the same material batch are not expected to yield equal results. Rather, it is expected that – if measurement processes are under quality control, traceable, and carry a reliable statement of the associated uncertainties – independent results are consistent within measurement uncertainties.

Although the nuclear material accountancy systems only reflect the measurement results and do not include the measurement uncertainties, these propagate with the physical measurements performed during the MBP and affect the confidence in the knowledge of physical stock values. As a consequence, the book values at the end of the MBP, depending solely on measurement results, may not equal the physical stocks, depending on both measurement results and associated uncertainties. Therefore, even though clerical errors, hidden stocks, or nuclear material gain, loss, or diversion do not affect the ledgers, the book values at the end of the MBP may legitimately be different from the physical stocks.

[98] Exception: The operator may perform mass measurements of material contained in items.

[99] Enrichment facilities transform nuclear materials from solid state to gas and back to solid; reprocessing facilities handle solid materials, turn them into liquid form and back to solid; in fuel fabrication facilities powder is blended, homogenised, pelletized, sintered and built into fuel elements.

We have defined this difference as MUF: the difference between the physical ending, *PE*, and the balance accountancy, *BA*. When taking a Physical inventory, nuclear operators of bulk-handling facilities must measure their stocks, compute the MUF, and declare it using the inventory change code MF according to Regulation 302/2005.

5.1 MUF and σ_{MUF} Assessment

The role of EURATOM safeguards is to assess the declared MUF against specific criteria, to satisfy itself that it appears to be originated by legitimate measurement uncertainties.

Nevertheless, according to the Commission recommendation 2009/120/EURATOM, nuclear operators should put in place a measurement control programme in order to ensure the validity of the measurement results and their uncertainties used for accountancy declarations. Therefore, prior to any analysis performed by EURATOM safeguards, it is the operators' primary responsibility to ensure that the NMAC system in place is able to demonstrate that the PE and the BA, despite their difference, are consistent within the global uncertainties associated to the measurement activities under quality assurance processes. The operators' measurement control programme must demonstrate appropriate instruments' performance, absence of measurement bias, the description of equipment and methods, and a solid quality assurance system.

In absence of an appropriate measurement control program, it may be challenging for an operator to set up an NMAC system able to compute global uncertainties that could justify the declared MUF.

Concerning the material balance verification activities, nuclear inspectors are responsible for the evaluation of the declared MUF significance, aiming at appreciating, with a certain confidence, whether or not there is an indication of diversion within the limitations of the verifications performed.

Assessing the MUF significance relies on a deep knowledge of the primary and secondary nuclear material flows, but also on independent knowledge of the measurement process and uncertainties affecting the declared nuclear material balances and inventories. Such knowledge may originate from independent measurement systems available to the inspectors, by EURATOM-owned equipment, and through on-site laboratory activities.

Where independent measurement systems are not available, the inspectorate may refer to the operator measurement systems, provided that it is authenticated and validated to be compliant in performance with the most recent international standards.

Where the use of operator measurement systems is not deemed appropriate, the evaluations may be based on the most recent ITVs and the instruments performance declared in the BTCs.

Such independent estimation of the uncertainty associated to the declared MUF allows the verification of its consistency with zero, namely that the PE and the BA are consistent within legitimate measurement uncertainties. The level of confidence relative to such statement strongly depends on whether EURATOM disposes of independent measurement systems, relies on assumptions on the operator systems performance, on ITVs, or is limited by BTC declarations.

As an example, the confidence level can be considered:

- Relatively high, if the declared MUF is found well justified by legitimate measurement uncertainties, defined either via operator measurement systems authenticated and compliant to modern standards, or via independent measurement systems available to EURATOM.

- Significantly lower, if the declared MUF appears to be legitimate when attributing BTC declared uncertainties to the whole material balance flow and inventory, rather than observed operational uncertainties.
- Definitely poor, if the declared MUF and its trend – concept explored below in section 5.2 – cannot be duly compared to measurement uncertainty due to scarce knowledge of either the nuclear material flows or the associated measurement methods.

The assessment of MUF significance is central to the MBE activities, and the evaluation context is framed by the MBP *N* starting with the initial inventory, I_i, and ending with the final inventory, I_f, according to the following principles.

At the end of the MBP *N-1*, assuming that both the inventory and the declared MUF were found acceptable, the operator establishes I_i, and during the course of the MBP *N* accounts for inputs *R* and outputs *S* from the MBA. In turn, the inspectors verify *R* and *S* against physical measurements and according to the inspection activities described above in section 4. Finally, the operator establishes I_f, takes a new physical inventory (PIT), evaluates the difference between *PE* and *BA*, declares and justifies the MUF. At this stage, the inspectors verify the declared physical inventory (PIV) and evaluate the declared MUF.

The MUF evaluation primarily consists in assessing whether its magnitude is acceptable when compared

(a) with the annual throughput[100],

(b) with the total inventory of materials,

(c) with its uncertainty σ_{MUF}, as defined above in section 3.4.

For the criteria (a) and (b), the acceptable limits are established as the most restrictive between facility performance indicators[101] and international standards of accountancy [8] reported in Table 1. These are used, in combination with the ITVs, to assess whether the facility measurement systems meet international standards, and therefore if the overall uncertainty accumulated over an MBP is such that the MUF magnitude appears legitimate. When closing a material balance, the δ_E values of Table 1, based on operational experience and depending on the type of bulk handing facility, are considered as reasonable measurement uncertainties relative to the amounts of material processed in normal conditions. As an example, a MUF declared to be higher than 0.5% of the annual throughput of a plutonium fabrication plant would appear unjustified by reasonable measurement uncertainties. Therefore, EURATOM would require that the operator investigates and provides an explanation of how the operational conditions deviated from normality in a way that can explain the outstanding MUF magnitude.

[100] The amount of nuclear material transferred out of the facility during the MBP of reference.

[101] Also expressed as Inventory Difference Action Level, namely a threshold for the MUF, set either by the operator or by plant performance in normal conditions, beyond which an internal investigation is required.

Table 1: Expected measurement uncertainty (relative standard deviation) associated with closing material balance.

Bulk handling facility type	δ_E
Uranium enrichment	0.002
Uranium fabrication	0.003
Plutonium fabrication	0.005
Uranium reprocessing	0.008
Plutonium reprocessing	0.01
Separate scrap storage	0.04
Separate waste storage	0.25

Beyond the criteria (a) and (b) dealing with overall plant performance, the criterion (c) requires relating the declared MUF to individual measurement results. These, propagated across the multiple measurement processes performed during the MBP, and relative to nuclear material transferred into the MBA, out of the MBA, or passing through different key measurement points (KMP) within the MBA, ultimately result in the combined uncertainty σ_{MUF}.

The σ_{MUF} computation method has an important role in the assessment of the MUF legitimacy. There exist two main σ_{MUF} computation approaches:

- The *bottom-up* approach, method of choice at the European Commission, is based on the GUM principles of instruments calibration and propagation of uncertainties relative to every component influencing the outcome of a measurement.
- The *top-down* approach, method of choice at the IAEA [9], is based on analysis of variance of observed operator-inspector differences, or paired-data.

Despite discussing the details of these approaches is beyond the scope of this lecture, it is important to note that the resulting σ_{MUF} is used to set the acceptable limits for the magnitude of the declared MUF, and to assess the plausibility of the uncertainty quantification provided by the operator. The current approach implemented at EURATOM safeguards requires that

$$MUF \leq k\sigma_{MUF}$$

where

- *k=2* is a threshold beyond which the operator would have to provide an explanation, as such a MUF magnitude would strongly limit the confidence in its legitimacy, and
- *k=3* is a threshold beyond which the operator would be requested to carry on an investigation and provide a specific report addressing such an outstanding MUF, very strongly limiting the confidence in its legitimacy;

In addition, the σ_{MUF} calculated by either methodology is used to assess the σ_{MUF} provided by the operator. In fact, operators may demonstrate the legitimacy of declared MUF, and the inspection activities may not raise any evidence indicating otherwise, although additional factors as clerical errors, hidden inventories, non-measured losses, and nuclear material diversion might still be contributing to the MUF or compensating one

another to some extent. For this reason, should the σ_{MUF} provided by the operator exceed significantly the EURATOM expectations based on the bottom-up approach, then both the operator's measurement control program and the quality management system would be questioned.

For this reason, the European Commission has complemented the safeguards verification activities with a broader system of audit. The synergy between inspections and audit processes is instrumental in the view of providing additional confidence in the safeguards conclusions. As mentioned in the syllabus paper on "*The basic principles of nuclear material management*", these two complementary approaches have different detection capabilities because they are based on different perspectives. While inspections focus on results aiming at evaluating past safeguards performances, audits focus on process control to stimulate continuous improvement; inspections focus on management of nuclear materials, while audits focus on management of resources.

In conclusion, these additional verification layers ensure that the operator is able to harness the operational uncertainties within a consistent NMAC system. Nevertheless, additional factors, including diversion, are still open for evaluation at this stage. Therefore, an additional set of material balance tests are performed to complement the assessment of MUF and σ_{MUF}.

5.2 MUF Trend, CU_{MUF}

The confidence level is further shaped by additional activities such as monitoring the trend of declared MUF values over several MBPs.

A legitimate MUF is expected to be positive, indicating an apparent gain of material over an MBP, or negative, indicating an apparent loss, with the same probability. Such behaviour is considered the indication of normal operating conditions, since the MUF results from the combination of random measurement uncertainties. In simple terms, it is not legitimate that consecutive MUF values do not spread around zero.

It is not rare that MUF values declared in subsequent MBPs, individually justified by legitimate measurement uncertainties, appear to indicate a systematic deviation of measurement results or a measurement bias.

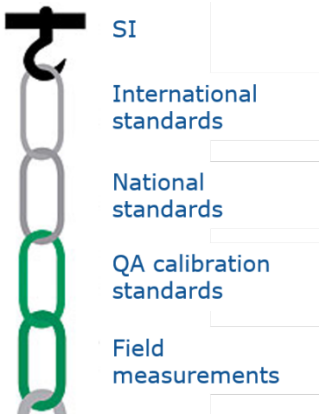
Therefore, EURATOM would require the operator to provide technical explanations if consecutive MUF declarations assume systematically positive or negative values. The algebraic sum of MUF values along a series of MBPs for a given MBA, or CU_{MUF}, provides an indication of the overall amount of material -apparently gained or lost- that is not under acceptable NMAC system and quality control.

In conclusion, the statistical evaluation of the CU_{MUF} is a valuable mean to reach a safeguards conclusion overcoming the limitations of MBP time divisions.

5.3 SRD Evaluation

An important element to gain confidence in the safeguards conclusion lies in the SRD evaluation and the investigation of traceability of declarations.

As discussed in section 3.3, transfers of nuclear materials across bulk handling facilities would require that both the shipper and the receiver perform measurements. Such transfers can be considered successfully accounted for if the two measurement results are consistent. However, when the two parties of the transfer are independent facilities, then an additional verification challenge is related to the implementation of independent measurement systems and procedures. Therefore, in addition to verify that shipper and receiver report consistent declarations, it is also necessary to ensure traceability of the declared results.



Metrological traceability requires an unbroken chain of calibrations that allows expressing a result relative to a reference standard, and ultimately to the International System of Units (SI).

A measurement result and the quantification of the associated uncertainty must be expressed in relative terms, with respect to a certified reference value. When shipper and receiver use different in-field references, these must be traceable back to the SI in order to *reconcile* their independency and compare the measurement results legitimately.

The difference in the measured values is called Shipper-Receiver difference, or SRD, and it must be declared by the use of the inventory change code DI, in conformity with the EURATOM regulation 302/2005. Such SRD may be caused by legitimate measurement uncertainties, but also conceal deliberate or unintentional nuclear material diversion. Therefore, the nuclear safeguards inspectorate must pay particular attention to assess the *comparability* of the measurement results provided by the shipper and by the receiver.

The evaluation of uncertainty estimation methods used by the nuclear operators and the quality of the measurement systems concerned are of crucial importance in this process, since the possibility of diversion through overestimation of uncertainties cannot be excluded.

It may happen that calibration chains are broken, and EURATOM safeguards cannot conclude, by means of statistical tools, the legitimacy of SRD declarations. In this case, the level of confidence associated with the final safeguards conclusion would be affected. Therefore, EURATOM requests and takes actions to verify the compliance of nuclear operators' measurement systems with latest international standards.

5.4 Evaluation of Special IC Codes

A further contribution to the level of safeguards confidence derives from the study of correlations between specific inventory change codes and declared MUF.

Inventory changes defined in the EURATOM regulation 302/2005 can be erroneously used, or intentionally employed to alter a MUF that would otherwise appear unjustified to EURATOM safeguards. Therefore, the First Layer Assessment activities outlined in section 4.1 are of paramount importance to ensure appropriate use of inventory changes candidate as MUF tuners.

The systematic monitoring of declarations such as *new measurement*, *transfer to waste* and *accidental gain or loss*, ensures that their use is technically justified and does not highlight undue correlations with, or tuning of, the declared MUF.

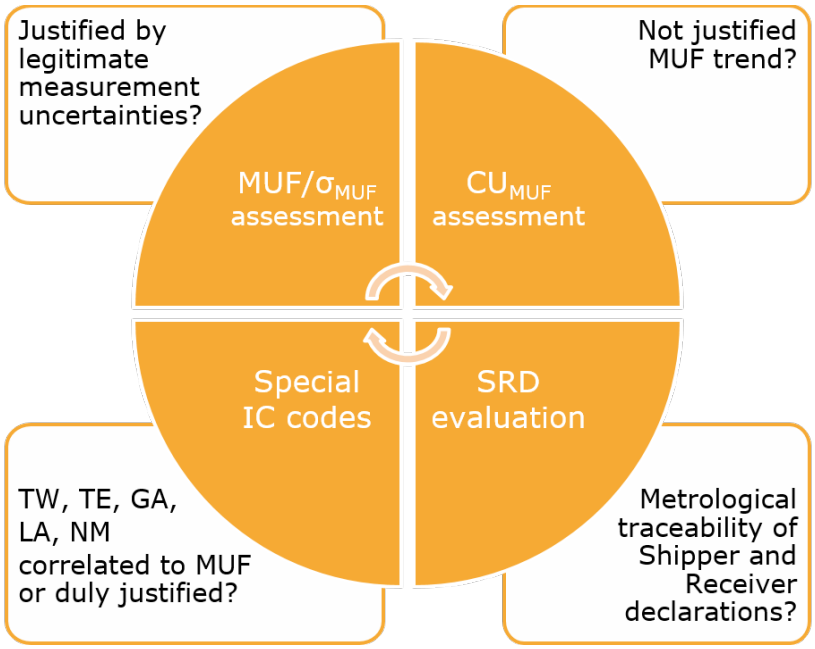


Figure 5: The Material Balance Evaluation processes.

6 Nuclear Safeguards Conclusions

The results of all conformity assessment activities carried out by EURATOM at nuclear installations lead to annual nuclear safeguards conclusions, drawn for every MBA and for each MBP.

Nuclear inspectors make use of expert knowledge of the specific installations to aggregate the results, in an iterative and peer-reviewed process, to conclude whether:

- There is a suspicion of diversion of nuclear materials from their intended, declared uses;
- The nuclear materials are managed, accounted for and controlled at an acceptable level of quality;
- The nuclear operators fulfilled all their nuclear safeguards obligations.

All safeguards conclusions are associated and expressed with a degree of confidence that depends on the extent to which all information were available and all conformity assessment activities could take place as planned to cover all the potential diversion and mismanagement scenarios.

The causes possibly limiting the confidence level for the nuclear safeguards conclusions range across equipment failures, missing information due to defective NMAC systems, restrictions to randomness of item sampling for measurements, and measurement uncertainties affected by undue environmental conditions.

To continuously improve the safeguards effectiveness, the conformity assessment activities are designed against the parameters related to low confidence levels for nuclear safeguards conclusions.

Once nuclear inspectors have proposed safeguards conclusions for each MBAs, these follow three rounds of consultations, from technical to management level, in order to ensure assessment homogeneity and proportionality across all the safeguarded installations.

Finally, safeguards conclusions are aggregated in the annual EURATOM safeguards report, which is submitted to the Commission's political level for endorsement.

7 Conclusions, Outlook and Future Implementation Challenges

Originating from the extraordinary legal framework provided by the EURATOM Treaty and its related secondary legislation, the EURATOM safeguards activities are based on well-defined assessment criteria that provide measurable and objective degrees of conformity. These are paired with elements of qualitative knowledge of the nuclear material flows and professional judgement of the implications that facility operations may have in terms of diversion risk. Both the quantitative and the subjective elements are combined evaluating a material balance, aiming, by means of detection capability, at non-diversion deterrence, dissuasion, and ultimately prevention.

The annual safeguards conclusion is a major output of the EURATOM activities, and aggregates the knowledge acquired through the safeguards verification activities. The conclusive statement is formulated in terms of confidence, expressing the degree of satisfaction in the evidence that no materials are diverted from their intended scopes, and all international obligations are complied with.

The aggregation of information stems from safeguards verification activities that are driven by counting and measuring processes. These must be performed meaningfully, yield traceable and reproducible results, and account for knowledge of qualitative nature, as *"Not everything that counts can be counted, and not everything that can be counted counts."*[93]

The current implementation of the Commission's nuclear safeguards strategy in the Community is described in two key Communications from the Energy Commissioners to the Commission, of 2004, on the *implementation of nuclear inspection and safeguards tasks*, and 2006, on the *implementation of nuclear safeguards within the European Union*.

Over the course of time, however, the nuclear safeguards landscape has evolved significantly due to political, economic and technological developments. Therefore, the Commission's Energy directorate safeguards approach and governance of EURATOM Safeguards Implementation must address the following emerging safeguards challenges:

1. **Decommissioning of individual nuclear installations**. The number of operational nuclear power plants in the EU is evolving and the nuclear fleet is ageing. Therefore, EURATOM safeguards must address additional challenges resulting from the decommissioning of individual nuclear installations. Accounting for recovered nuclear material and determining the conditions under which such materials may be treated under EURATOM safeguards will require dedicated safeguards measures.
2. **Deep geological repositories**. In line with their advancement in the nuclear fuel cycle and the related increase in nuclear waste, EURATOM Member States are moving towards the establishment of deep geological repositories for disposal of high-level radioactive waste, typically combined with encapsulation plants. Installations of this type are expected to become operational in Finland, Sweden and France before 2030. Therefore, the results of the ongoing development of safeguards approaches for geological repositories and encapsulation plants are expected to become a constitutive part of EURATOM Safeguards.
3. **Small holders**. The number of European small nuclear material holders is constantly increasing and the EURATOM Treaty does not foresee any *de minimis* amounts. Therefore, EURATOM safeguards apply to all quantities and all holders of nuclear materials, including those related to non-nuclear industry, and to medical and research applications. In this context, strengthening the EURATOM collaboration with member states and their national authorities is considered instrumental to identify and monitor small holders.

4. **Closeness of EURATOM Safeguards operations to their political mandate**. In line with the current political challenges, EURATOM safeguards operations must evolve remaining closely tied to their political mandate. Therefore, the EURATOM safeguards approach and governance must demonstrate increasing efficiency, effectiveness and transparency. A renewed EURATOM governance approach – based on the concept of safeguards confidence as discussed in this lecture – is expected to align, at political level, the obligations under Article 77 of the EURATOM Treaty with these new challenges.

To address these challenges, EURATOM safeguards value the ESARDA patrimony of knowledge and relationships as a precious asset. A continued dialogue and cooperation between safeguards institutions and the research community is expected to foster the safeguards evolution and to respond to the current and future political challenges.

8 Acknowledgements

The author is grateful to Wolfgang Kilb, Oscar Alique, and Jean Coadou for their valuable contributions. They have ensured that this lecture reflects the European legal setting, that it is consistent with the European Commission's material balance evaluation practices, corresponds to the EURATOM safeguards structure and is in line with the underlying policy framework.

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Random Sampling in Nuclear Material Safeguards

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1. Introduction

By general agreement international nuclear material safeguards is organized in such a way, that the plant operators generate all the data necessary for the establishment of a material balance, that the inspectors verify the operators' data with the help of independent measurements and that – if there are no statistically significant differences between the operators' data and the inspectors' findings – the material balance is established with the help of the operators' data.

In this chapter the present state of data verification is discussed. While most of the chapter is a modified and extended version of the work presented in [1] and in the first edition of this Course Syllabus, the game theoretical model in section 3.2 and its solution is presented here the first time. Two kinds of sampling procedures will be considered. With the help of the *variables sampling* [2] procedure, which considers measurement errors, the expected differences between the operators' reported data and the inspectors' findings are quantitatively evaluated. The *attribute sampling* [3] procedure permits only qualitative statements about the reported data. In addition, *variables sampling in the attribute and in the variable mode* will be sketched, since it has raised some discussion over the years; see e.g., [4], [5] and [6].

In the following we will consider primarily the verification of inventory data, first, because it is easier from a methodological point of view, and second, because it represents an especially important part of safeguards: whereas flow measurement data sometimes can be verified by comparing shipper and receiver data, there is nothing which can replace inventory data verification using independent measurements. Data verification presents a *statistical problem* because of the random sampling procedure and, in case of variable sampling, because of the existence of statistical measurement errors. Furthermore, since in the latter case at the end of the verification procedure a decision has to be taken whether the data of the operator are accepted, data verification in safeguards basically is a *test problem*. An inspector may also be interested in estimating possible defects sizes; see [7]; since, however, their use is not clear in international safeguards, estimation is not discussed here. Finally, contrary to conventional statistical problems like quality control, there is a conflict situation between an operator who may falsify data – otherwise there would be no reason for verifying his data – and the safeguards authority which has to detect an eventual falsification. This means that data verification also represents a *game theoretical problem* where it is assumed that the operator – if at all – will falsify data in such a way that he minimizes the detection probability and that the inspector maximizes it, with an agreed false alarm probability in case of variable sampling.

The main findings will be formulated as Theorems. Proofs will not be given since otherwise this chapter would become exceedingly lengthy, instead they can be found in the literature. For the same reasons numerical examples will not be given even though some readers may sadly miss them. These two remarks raise the question who the client of this chapter is, researchers, practitioners or anyone in between. We leave it to the lecturers of the courses to feel free to select or deepen the material presented here, and eventually to include practical examples for the benefit of the respective audience.

2 Attribute Sampling

According to general understanding [3] "inspection by attributes is inspection whereby either the unit of product is classified simply as defective or nondefective, or the number of defects in the unit of product is counted, with respect to a given requirement or set of requirements". In the context to be discussed here it is assumed that someone has reported a set of data, that an inspector verifies a subset of these data with the help of independent observations, and that for each set of data – reported and verified – it can be stated, without committing any error, whether or not these two data sets are consistent. It should be mentioned that the reported data may be sealed items, in which case data verification then means checking the integrity of the seals.

2.1 One Class of Material: One Measurement Device

Let us assume that N data have been reported by an operator and that n data are verified by an inspector with the help of independent observations on a random sampling basis. The question arises as to how large the number n of observations has to be if r data are falsified and at least one falsification has to be detected with a given probability. The probability of detecting at least one falsified datum is one minus the probability of detecting no falsified data. In case of drawing without replacement this probability is determined by the hypergeometric distribution, see e.g., [8], and is given by

$$\begin{aligned} 1-\beta(n,r) &= \mathbb{P}(\{\text{having no defects in the sample}\}) \\ &= 1-\begin{cases} \dfrac{\binom{r}{0}\binom{N-r}{n-0}}{\binom{N}{n}} & for \quad n \le N-r \\ 0 & for \quad n > N-r \end{cases} \end{aligned} \tag{1}$$

which can also be written as

$$1-\beta(n,r) = 1-\prod_{i=0}^{r-1}\left(1-\frac{n}{N-i}\right) . \tag{2}$$

If the number of falsified data is small compared to the total number, i.e., if $r \ll N$, then we get

$$1-\beta(n,r) \approx 1-\prod_{i=0}^{r-1}\left(1-\frac{n}{N}\right) = 1-\left(1-\frac{n}{N}\right)^{r} =: 1-\beta_1(n,r) . \tag{3}$$

Let us consider the case of *drawing with replacement*: If only one datum is "drawn", then the probability of getting no falsified data is $1-r/N$, therefore the probability of detecting at least one falsified datum is

$$1-\beta_2(n,r) := 1-\left(1-\frac{r}{N}\right)^{n} . \tag{4}$$

Since the difference between drawing with and without replacement should be negligible in case of a small sample size ($n \ll N$), one should get this formula also from (1). In fact, since (1) is symmetric in n and r we can write (2) also as

$$1 - \beta(n,r) = 1 - \prod_{j=0}^{n-1}\left(1 - \frac{r}{N-j}\right)$$

which simplifies for $n \ll N$, using (4), to

$$1 - \beta(n,r) = 1 - \prod_{j=0}^{n-1}\left(1 - \frac{r}{N-j}\right) \approx 1 - \prod_{j=0}^{n-1}\left(1 - \frac{r}{N}\right) = 1 - \beta_2(n,r)\,.$$

Let us answer the question posed at the beginning of this section: For $n \ll N$ we get from (3)

$$n_1 = N\left(1 - \sqrt[r]{\beta_1}\right) \tag{5}$$

whereas we get for $n \ll N$ from (4)

$$n_2 = \frac{\ln \beta_2}{\ln(1 - r/N)}\,. \tag{6}$$

For a given value of β_2 the value of n_2 depends only on the ratio $f = r/N$, whereas n_1 depends on r and N separately. If we fix the ratio f, then, using (5), n_1 can be written as

$$n_1 = N\left(1 - \sqrt[Nf]{\beta_1}\right).$$

For fixed values of f and β_1 we obtain, using the rule of L'Hospital twice, see, e.g., [9], the following asymptotic value of n_1:

$$n_1^{\infty} := \lim_{N\to\infty} n_1 = -\frac{\ln \beta_1}{f}\,. \tag{7}$$

Furthermore, because of $\ln(1-f) = -f$ for $f \ll 1$ we get from (6) and (7), and with $\beta_1 = \beta_2$ and for $f \ll 1$

$$n_2 = n_1^{\infty}\,,$$

i.e., identical sample sizes for large sets N of data.

2.2 One Class of Material: Two Measurement Devices

For many years it has been the practice in the verification of reported data in certain classes (such as fresh reactor fuel elements) to use a multi-level sampling procedure. With the aid of an exact but time-consuming method a relatively small number of measurements are made to determine whether some data were falsified by small amounts (so-called bias defects). An inexact but quick method is used to check if a smaller number of data have been falsified by large amounts (so-called gross defects).

If one assumes that an inspector has only a limited amount of time, the question immediately arises as to the most efficient number of samples to choose for each measurement method. Hereby one must take into account that the operator, should he wish to deliberately falsify the data, will do so in such a way as to minimize the chance of detection. In other words, the problem is one of statistics, due to the random sampling of items for verification and to the unavoidable measurement errors, but also one of strategy, because of the essentially antagonistic nature of verification. A game-theoretical analysis is therefore needed. The problem described here was treated some time ago on a heuristic basis, among others by [4] and [5]. More recently, interest in the problem has been renewed, with [6] presenting new heuristic approaches.

We assume that N material content data for similar items or batches are reported to an inspector, who then verifies them by independently measuring a random sample of the items. He has at his disposal an accurate but time-consuming measurement procedure as well as a faster but less accurate method with which he can detect large falsifications of the data. The accurate method of course will also detect large falsifications. For both methods it is assumed that if a falsified item is presented, then the method will identify it as defective with probability one, i.e., an attribute test is performed for both kind of items (falsified by gross defect and bias defect). This implies that statistical errors of the first and second kind, see, e.g., [10], cannot occur.

If the inspector verifies n_1 data with the accurate procedure and n_2 with the less accurate procedure, and if r_1 data are falsified by a small and r_2 data by a large amount, then the overall detection probability, i.e., the probability of detecting at least one falsification, is for sampling with replacement given by

$$1 - \beta(n_1, n_2; r_1, r_2) \coloneqq 1 - \left(1 - \frac{r_1 + r_2}{N}\right)^{n_1} \left(1 - \frac{r_2}{N}\right)^{n_2} . \tag{8}$$

Here it should be noted that in a real situation the inspector will sample the items without replacement, at least for a given measurement method. Since the difference is negligible for small samples, we shall continue to restrict the discussion to sampling with replacement.

Now we shall assume that the operator falsifies his data by a total amount μ, his goal quantity. Let μ_1 and μ_2 be the small and large individual falsifications respectively. Then the operator's strategy set is given by

$$Y_\mu \coloneqq \{(r_1, r_2) \in \mathbb{R}_+ \times \mathbb{R}_+ : \mu_1 r_1 + \mu_2 r_2 = \mu\} . \tag{9}$$

Note that because μ_1, μ_2 and μ are given, the $=$ sign in (9) can only be assured if r_1 and r_2 are assumed to be continuous variables. Similarly, we assume that the total amount of time available to the inspector for his measurements is ε, and that ε_i is the time required for the verification of a single datum with the ith method, $i = 1,2$. Thus, the inspector's strategy set is given by

$$X_\varepsilon \coloneqq \{(n_1, n_2) \in \mathbb{R}_+ \times \mathbb{R}_+ : \varepsilon_1 n_1 + \varepsilon_2 n_2 = \varepsilon\} . \tag{10}$$

In (10) the sample sizes n_1 and n_2 are assumed to be real numbers due the $=$ sign. Note that all parameters of the problem, i.e., μ_1, μ_2 and μ as well as $\varepsilon_1, \varepsilon_2$ and ε are assumed to be known to both the inspector and the operator.

A rational behavior solution to this problem involves the determination of a saddle point $(\vec{n}^*;\vec{r}^*) := (n_1^*, n_2^*; r_1^*, r_2^*)$ of the detection probability $1-\beta(n_1,n_2;r_1,r_2)$ in the strategy space $X_\varepsilon \times Y_\mu$ of the two players defined by

$$1-\beta(n_1,n_2;r_1^*,r_2^*) \le 1-\beta(\vec{n}^*;\vec{r}^*) \le 1-\beta(n_1^*,n_2^*;r_1,r_2)$$

for all $(n_1,n_2;r_1,r_2) \in X_\varepsilon \times Y_\mu$. If the sample sizes n_1 and n_2 and the number of falsified items r_1 and r_2 are assumed to be continuous variables, then the game theoretical solution is given in

THEOREM 1 (see [11])

Let the strategy sets of the inspector and the operator be given by (10) and (9) and let the payoff to the inspector be given by (8). The game theoretical solution of the zero-sum game $\left(X_\varepsilon, Y_\mu, 1-\beta(r_1,r_2;n_1,n_2)\right)$ is given as follows: Let C be defined by

$$C := \varepsilon_1\mu_1(\beta^*)^{\varepsilon_1/\varepsilon} + \varepsilon_2(\mu_2-\mu_1)(\beta^*)^{\varepsilon_2/\varepsilon}.$$

Then the optimal strategies of the inspector and the operator are given by

$$\begin{aligned} n_1^* &= \frac{\varepsilon}{C}\,\mu_1\,(\beta^*)^{\varepsilon_1/\varepsilon} \quad \text{and} \quad n_2^* = \frac{\varepsilon}{C}\,(\mu_2-\mu_1)\,(\beta^*)^{\varepsilon_2/\varepsilon} \\ r_1^* &= N\left((\beta^*)^{\varepsilon_2/\varepsilon} - (\beta^*)^{\varepsilon_1/\varepsilon}\right) \quad \text{and} \quad r_2^* = N\left(1-(\beta^*)^{\varepsilon_2/\varepsilon}\right) \end{aligned}, \tag{11}$$

and the optimal detection probability $1-\beta^*$ is implicitly given by

$$\mu = N\left(\mu_2 - \mu_1(\beta^*)^{\varepsilon_1/\varepsilon} - (\mu_2-\mu_1)(\beta^*)^{\varepsilon_2/\varepsilon}\right). \tag{12}$$

Note, that the "systems parameters" μ, ε and β^* are related to each other by (12), which means that if two are given, the third can be determined.

If β^* from (12) fulfils for $i = 1,2$ the relation

$$(\beta^*)^{\varepsilon_i/\varepsilon} \approx 1 - \frac{\varepsilon_i}{\varepsilon}(1-\beta^*), \tag{13}$$

then (12) directly yields

$$1-\beta^* \approx \frac{1}{N}\frac{\varepsilon\,\mu}{\varepsilon_1\,\mu_1 + \varepsilon_2\,(\mu_2-\mu_1)}.$$

and the sample sizes n_1^* and n_2^* in (11) reduce for $\varepsilon_1 \ll \varepsilon$ (recall $\varepsilon_2 < \varepsilon_1$) to

$$n_1^* \approx \frac{\varepsilon}{\epsilon_1\,\mu_1 + \epsilon_2\,\dfrac{1-(1-\beta^*)\,\epsilon_2/\epsilon}{1-(1-\beta^*)\,\epsilon_1/\epsilon}\,(\mu_2-\mu_1)}\,\mu_1 \approx \frac{\varepsilon}{\varepsilon_1\,\mu_1 + \varepsilon_2\,(\mu_2-\mu_1)}\,\mu_1,$$

and similarly

$$n_2^* \approx \frac{\varepsilon}{\varepsilon_1\mu_1 + \varepsilon_2(\mu_2-\mu_1)}\,(\mu_2-\mu_1),$$

which confirms what might have been expected before a quantitative analysis: The sample size n_1^* for the exact method is proportional to the small falsification μ_1, the sample size n_2^* for the inexact method to the large falsification, if we take $\mu_2 - \mu_1 \approx \mu_2$. Note that in the approximations n_1^* and n_2^* are independent of the total falsification μ.

The treatment in this section was made under the assumption that statistical errors of the first and second kind resulting from measurement error could be neglected. If these errors are taken into account, then a different analysis to the one presented here is required; see [11].

2.3 Several Classes of Material

Let us assume that there are K classes of material and that the i-th class contains N_i, $i = 1, \dots, K$, batches, the data of which are reported to an inspector. Different classes are characterized by their batch numbers, by the material contents of the batches, and by the efforts ε_i of the inspector for verifying one datum with an independent measurement method. As in the preceding section an attribute test is performed in each class which identifies a falsified item as falsified with probability one, i.e., statistical errors are excluded. Furthermore, let us assume that the inspector has the total inspection effort ε at his disposal in order to verify n_i data in the i-th class, $i = 1, \dots, K$, which means the inspector's strategy set is given by

$$X_\varepsilon := \left\{ (n_1, \dots, n_K) \in \mathbb{R}_+^K : \sum_{i=1}^{K} \varepsilon_i n_i = \varepsilon \right\}. \tag{14}$$

Note that, as in last section the sample sizes are assumed to be continuous variables due to the equality sign in (14).

Finally, we assume in which way the operator will – if at all – falsify the reported data:

DEFINITION 1 (see [12])

We call *model B* that set of falsification strategies which contains all possibilities of the operator to falsify r_i data of the i-th class by the amounts $\mu_i \leq \mu_{i,max}$, $i = 1, \dots, K$, which are supposed to be known to the inspector such that the data are falsified by the total amount μ of material, i.e., the operator's strategy set is given by

$$Y_\mu := \left\{ (r_1, \dots, r_K) \in \mathbb{R}_+^K : \sum_{i=1}^{K} \mu_i r_i = \mu \right\}. \tag{15}$$

Note that in (15) the r_i are treated again as continuous variables. The values of the parameters $\varepsilon, \varepsilon_i, \mu, \mu_i$, $i = 1, \dots, K$, are assumed to be known to both the inspector and the operator.

The overall probability of detecting at least one falsification is, in case of drawing with replacement, for any $(n_1, \dots, n_K) \in X_\varepsilon$ and $(r_1, \dots, r_K) \in Y_\mu$ given by

$$1-\beta(n_1,\dots,n_K;r_1,\dots,r_K) \coloneqq 1-\prod_{i=1}^{K}\left(1-\frac{r_i}{N_i}\right)^{n_i}. \tag{16}$$

The problem to be solved is to determine that distribution of the total inspection effort ε on the several classes which maximizes the overall probability of detecting at least one falsification, under the assumption that the operator falsifies the data in the way which is most favorable to him, i.e., which minimizes the probability of detection.

If the sample sizes $(n_1,\dots,n_K)$ and the number of falsified items $(r_1,\dots,r_K)$ can be considered as continuous variables, then the game theoretical solution in case of drawing with replacement is given in

THEOREM 2 (see [12], [13], [14])

Let the strategy sets of the inspector and the operator be given by (14) and (15) and let the payoff to the inspector be given by (16). The game theoretical solution of the zero-sum game $\left(X_\varepsilon, Y_\mu, 1-\beta(n_1,\dots,n_K;r_1,\dots,r_K)\right)$ is given as follows: The optimal strategies of the inspector and the operator are, for any $i=1,\dots,K$, given by

$$n_i^* = \frac{\varepsilon}{\sum_{j=1}^{K}\mu_j\,\varepsilon_j\,N_j\,(\beta^*)^{\varepsilon_j/\varepsilon}}\,\mu_i\,N_i\,(\beta^*)^{\varepsilon_i/\varepsilon} \quad \text{and} \quad r_i^* = N_i\left(1-(\beta^*)^{\varepsilon_i/\varepsilon}\right), \tag{17}$$

and the optimal detection probability $1-\beta^*$ is implicitly given by

$$\mu = \sum_{i=1}^{K}\mu_i\,N_i\left(1-(\beta^*)^{\varepsilon_i/\varepsilon}\right). \tag{18}$$

It can be seen by implicit differentiation with respect to μ_i that $1-\beta^*$ is a monotonically decreasing function of μ_i. This means that the operator will falsify as large as possible values of μ_i, i.e., $\mu_i=\mu_{i,max}$, $i=1,\dots,K$.

If all the class-specific verification efforts are equal, $\varepsilon_i=\varepsilon_1$ for $i=2,\dots,K$ we get with

$$n \coloneqq \frac{\varepsilon}{\varepsilon_1}, \qquad N \coloneqq \sum_{i=1}^{K}N_i, \qquad r^* \coloneqq \sum_{i=1}^{K}r_i^* = \frac{\mu\,N}{\sum_{i=1}^{K}\mu_i\,N_i}, \tag{19}$$

from (18)

$$\beta^* = \left(1-\frac{r^*}{N}\right)^n,$$

and from (17)

$$n_i^* = \frac{n\,r^*}{\mu\,N}\,\mu_i\,N_i, \quad r_i^* = \frac{r^*}{N}N_i, \quad i=1,\dots,K,$$

which means that both players behave in this case as if there were only one class consisting of N items, r^* of which are falsified and n verified.

If (13) is assumed for $i = 1, \dots, K$, then from (18) we get

$$1 - \beta^* \approx \frac{\varepsilon\, \mu}{\sum_{j=1}^{K} \mu_j\, \varepsilon_j\, N_j}$$

and (17) yields

$$n_i^* \approx \frac{\varepsilon}{\sum_{j=1}^{K} \mu_j\, \varepsilon_j\, N_j}\, \mu_i\, N_i, \quad r_i^* \approx \frac{\mu}{\sum_{j=1}^{K} \mu_j\, \varepsilon_j\, N_j}\, \varepsilon_i\, N_i, \quad i = 1, \dots, K\,.$$

This solution, which was obtained long time ago, see [15], allows an intuitive interpretation: The sample sizes n_i^* of the inspector have to be proportional to the maximally possible data falsifications in the various classes; the number of falsified data r_i^* of the operator have to be proportional to the inspector's efforts for verifying all data in the various classes.

2.4 The IAEA Formula

In Theorem 2 the case of sampling with replacement has been analyzed. Because the inspector usually does sampling without replacement, we consider this case now. Using (1) – (3), the overall probability of detecting at least one falsification can, for any $(n_1, \dots, n_K) \in X_\varepsilon$ and $(r_1, \dots, r_K) \in Y_\mu$, be approximated as follows:

$$1 - \prod_{i=1}^{K} \frac{\binom{r_i}{0}\binom{N_i - r_i}{n_i - 0}}{\binom{N_i}{n_i}} = 1 - \prod_{i=1}^{K} \prod_{j=0}^{r_i - 1} \left(1 - \frac{n_i}{N_i - j}\right) \approx 1 - \prod_{i=1}^{K} \prod_{j=0}^{r_i - 1} \left(1 - \frac{n_i}{N_i}\right) \tag{20}$$

$$= \quad 1 - \prod_{i=1}^{K} \left(1 - \frac{n_i}{N_i}\right)^{r_i} =: 1 - \beta(n_1, \dots, n_K; r_1, \dots, r_K)\,.$$

If, instead of the payoff (16) to the inspector the approximation (20) is used, and if the sample sizes $(n_1, \dots, n_K)$ and the number of falsified items $(r_1, \dots, r_K)$ can be considered as continuous variables, then the game theoretical solution is given in

THEOREM 3 (see [13], [14])

Let the strategy sets of the inspector and the operator be given by (14) and (15) and let the payoff to the inspector be given by (20). The game theoretical solution of the inspector leadership[102] zero-sum game $\left(X_\varepsilon, Y_\mu, 1 - \beta(n_1, \dots, n_K; r_1, \dots, r_K)\right)$ is given as follows: Let

$$\varepsilon \le \min_{i=1,\dots,K} \varepsilon_i\, N_i \quad \text{and} \quad \mu \ll \min_{i=1,\dots,K} \mu_i\, N_i\,. \tag{21}$$

[102] An inspector leadership (Stackelberg) game is a game where the inspector announces his strategy to the operator in a credible way. In such a game a strategy of the operator is a function of the strategies of the inspector. For the sake of simplicity in Theorem 3 we have presented only the optimal strategy of the operator for the case that the inspector plays his optimal strategy.

Then the optimal strategies of the inspector and the operator are for $i = 1, \dots, K$ given by

$$n_i^* = N_i \left(1 - (\beta^*)^{\mu_i/\mu}\right), \quad i = 1, \dots, K$$
$$(r_1, \dots, r_K) \in \left\{ \left(\frac{\mu}{\mu_1}, 0, \dots, 0\right), \left(0, \frac{\mu}{\mu_2}, 0, \dots, 0\right), \dots, \left(0, \dots, 0, \frac{\mu}{\mu_K}\right) \right\}, \tag{22}$$

and the optimal detection probability $1 - \beta^*$ is implicitly given by

$$\varepsilon = \sum_{i=1}^{K} \varepsilon_i \, N_i \left(1 - (\beta^*)^{\mu_i/\mu}\right). \tag{23}$$

Note that (18) has the same structure as (23): ε and μ as well as ε_i and μ_i, $i = 1, \dots, K$, have just to be exchanged.

Also note that the assumptions (21), which have no equivalent in Theorem 2, are due to the sampling without replacement scheme and to approximation (20). Again, the inspector is on the safe side to assume that the operator will prefer to choose the μ_i as large as possible, i.e., $\mu_i = \mu_{i,max}$, $i = 1, \dots, K$.

Let us mention that Theorem 3 is a game theoretical solution only if – as in Theorems 1 and 2 – the variables n_i and r_i for $i = 1, \dots, K$ are assumed to be continuous variables. Here, however, additionally an approximation of the true detection probability, i.e., the first term in (20), has to be utilized.

For uniform falsification across all classes, i.e., $\mu_i = \mu_1$ for $i = 2, \dots, K$, we get by (19)

$$r^* = \sum_{i=1}^{K} r_i^* = \frac{\mu}{\mu_i} \quad for \;\; i = 1, \dots, K$$

and thus by (22)

$$n^* := \sum_{i=1}^{K} n_i^* = \sum_{i=1}^{K} N_i \left(1 - (\beta^*)^{1/r^*}\right),$$

and hence with $N := \sum_{i=1}^{K} N_i$,

$$\beta^* = \left(1 - \frac{n^*}{N}\right)^{r^*}.$$

This solution can again be considered as the approximate solution of a one-class problem with N data in total, r^* of which are falsified and n^* verified.

If the inspection efforts are uniform across the classes, i.e., $\varepsilon_i = \varepsilon_1$ for $i = 2, \dots, K$, then the sample sizes in Theorem 3 reduce to a solution to the attribute sampling problem which has come to be known as the "IAEA formula"; see, e.g., [16] and [17]. It is used extensively by the International Atomic Energy Agency (IAEA) in routine inspections under its various non-proliferation agreements.

Originally, this formula was obtained heuristically, and the argumentation will be outlined here as it throws some light on Theorem 3. Again, we assume n_i and r_i, $i = 1, \dots, K$, are treated as continuous variables. Let

r_i, $i = 1, \dots, K$, be the number of falsified data in the i-th class, if the total falsification μ is confined to that class, i.e.,

$$r_i = \frac{\mu}{\mu_i}, \qquad i = 1, \dots, K. \tag{24}$$

Then the approximate non-detection probability in that class is, using (3),

$$\beta_i \approx \left(1 - \frac{n_i}{N_i}\right)^{r_i} = \left(1 - \frac{n_i}{N_i}\right)^{\mu/\mu_i}, \qquad i = 1, \dots, K. \tag{25}$$

Should the operator, on the other hand, wish to distribute his activities over the K classes such that

$$\mu = \sum_{i=1}^{K} \tilde{\mu}_i \,,$$

where $\tilde{\mu}_i$ is the total falsification in the i-th class, then the number of items he must falsify in each class is

$$\tilde{r}_i = \frac{\tilde{\mu}_i}{\mu_i}, \qquad i = 1, \dots, K.$$

The approximate non-detection probability for the i-th class is in analogy to (25), using (24), given by

$$\tilde{\beta}_i \approx \left(1 - \frac{n_i}{N_i}\right)^{\tilde{r}_i} = \left(1 - \frac{n_i}{N_i}\right)^{\tilde{\mu}_i/\mu_i} = \left(1 - \frac{n_i}{N_i}\right)^{\tilde{\mu}_i r_i/\mu}, \qquad i = 1, \dots, K, \tag{26}$$

If the inspector now determines his class sample sizes n_i^* such that he obtains for each class a required non-detection probability β_{req} under the assumption that the total amount is falsified in *one* stratum, i.e., $\beta_i = \beta_{req}$, then (25) yields

$$\beta_{req} = \beta_i \approx \left(1 - \frac{n_i^*}{N_i}\right)^{r_i}, \qquad i = 1, \dots, K. \tag{27}$$

Now the required non-detection probability is still guaranteed if the falsification had actually been distributed in some arbitrary way over the K classes: Using (26) and (27) we get

$$\prod_{i=1}^{K} \tilde{\beta}_i \approx \prod_{i=1}^{K} \left(1 - \frac{n_i^*}{N_i}\right)^{\tilde{r}_i} = \prod_{i=1}^{K} \left(1 - \frac{n_i^*}{N_i}\right)^{\tilde{\mu}_i r_i/\mu} = \prod_{i=1}^{K} \left(\beta_{req}\right)^{\tilde{\mu}_i/\mu} = \left(\beta_{req}\right)^{\sum_{i=1}^{K} \tilde{\mu}_i/\mu} = \beta_{req} \,.$$

The sample sizes n_i^* obtained by this heuristic result, applied as we have said extensively by the IAEA, is nothing other than formula (22) of Theorem 3, as can be seen by using (25) with $\beta_i = \beta_{req}$ for $i = 1, \dots, K$.

3. Variable Sampling

Contrary to attribute sampling procedures, where the size of a defect was not taken into account, since any defect was assumed to be detected without committing measurement errors, variables sampling inspection has been defined as follows: "inspection wherein a specified quality characteristic on a unit of product is measured on a continuous scale, such as pounds, inches, feet per second etc., and a measurement is recorded. The unit of product is the entity of product inspected in order to determine its measurable quality characteristic... The quality characteristic for variables inspection is that characteristic of a unit of product that is actually measured to determine conformity with a given requirement"; see [2].

In our case we assume that the operator has reported a set of data, that an inspector verifies a subset of these data with the help of independent measurements, and that for each pair of data in general it cannot be decided without committing errors whether a difference between the two data is due to measurement errors or to differences between the true values.

3.1 One Class of Material: One Measurement Device

Let us assume that N data $X_1, \dots, X_N$ have been reported by an operator, and that n with $1 \leq n \leq N$ data are verified by an inspector with the help of independent measurements $Y_1, \dots, Y_n$ on a random sampling basis. Note that it can be assumed without loss of generality that the first n data are verified; see [14]. Since the inspector is not interested in the true values of the random variables X_i or Y_i, but only in the deviations between corresponding reported and independently measured data, he will construct his test procedure based on the differences of the corresponding data:

DEFINITION 2 (see [12], [14])

The differences $Z_i := X_i - Y_i$ between the operator's reported data X_i and the independent measurements Y_i of the inspector are assumed to be independently and identically normally distributed random variables with variances

$$\mathbb{V}(Z_i) = \mathbb{V}(X_i - Y_i) = \mathbb{V}(X_i) + \mathbb{V}(Y_i) =: \sigma^2, \quad i = 1, \dots, n,$$

and with the expectations

$$\mathbb{E}(Z_i) = \begin{cases} 0 & \text{under} \quad H_0 \\ \mu_i > 0 & \text{under} \quad H_1 \end{cases}, \quad i = 1, \dots, n,$$

where H_0 is the null hypothesis (no data falsification) and H_1 is the alternative hypothesis (falsification of the i-th reported datum by the amount μ_i). □

Because the operator is assumed to want to acquire the goal amount μ by removing material from the batches represented by the data $X_1, \dots, X_N$, his strategy set Y_μ is given by

$$Y_\mu := \left\{ (\mu_1, \dots, \mu_N) \in \mathbb{R}^N_{\geq 0} : \sum_{i=1}^{N} \mu_i = \mu \right\}. \tag{28}$$

Note that the system parameters μ, σ and α are known both to the inspector and the operator. Also note that Definition 2 assumes that systematic measurement errors are ignored.

As mentioned, the inspector verifies the first n data by taking independent measurements. The evaluation of these measurements is done using a statistical test procedure, which is a function that maps the observations of the random variables Z_i onto one of the two alternatives H_0 or H_1; see [8] or [14]. The critical region C associated with the test is the set of all observations of the form $(z_1, \ldots, z_n)$ which lead to the rejection of H_0. Thus, the detection probability, i.e., the probability of accepting H_1 if it is true, is defined by $\mathbb{P}_{H_1}\big((Z_1, \ldots, Z_n) \in C\big)$.

According to standard practice we are looking for that test procedure (optimal test) which maximizes the detection probability $\mathbb{P}_{H_1}\big((Z_1, \ldots, Z_n) \in C\big)$. For a fixed value of the false alarm probability α, i.e., the probability of accepting H_1 if H_0 is true, again, we assume that the operator – if at all – will falsify all data by the total amount μ in such a way that the detection probability is minimized.

In case of the *maximum* sample size $n = N$, the detection probability is given by

$$1 - \beta(C; \mu_1, \ldots, \mu_N) := \mathbb{P}_{H_1}\big((Z_1, \ldots, Z_N) \in C\big) = \int_{(z_1, \ldots, z_N) \in C} \frac{1}{\left(\sqrt{2\pi}\sigma\right)^N} \exp\left(-\frac{1}{2\,\sigma^2} \sum_{i=1}^{N} \left(z_i - \mu_i\right)^2\right) dz_1 \ldots dz_N \,. \tag{29}$$

The game theoretical solution is presented in

THEOREM 4 (see [14])

Let the inspector's strategy set Δ_α be the set of all test procedures with a given false alarm probability α, let the operator's strategy set be given by (28), and let the payoff to the inspector be the detection probability given by (29). The game theoretical solution of the zero-sum game $\left(\Delta_\alpha, Y_\mu, 1 - \beta(C; \mu_1, \ldots, \mu_N)\right)$ is given as follows: An optimal strategy of the inspector is given by the test procedure with the critical region

$$C^* := \left\{ (Z_1, \ldots, Z_N) : \sum_{i=1}^{N} Z_i > \sqrt{N}\, \sigma\, U(1 - \alpha) \right\}, \tag{30}$$

where $U(\cdot)$ is the inverse of the standard normal distribution, and an optimal strategy of the operator by the uniformly distributed falsification

$$\mu_i^* = \frac{\mu}{N}, \quad i = 1, \ldots, N \,.$$

The optimal detection probability $1 - \beta^*$ is

$$1 - \beta^* = \Phi\left(\frac{1}{\sqrt{N}}\, \frac{\mu}{\sigma} - U(1 - \alpha)\right). \tag{31}$$

Equation (30) shows that the statistic, i.e., the function of the observed data, of the optimal test is the so-called D-statistic

$$D := \sum_{i=1}^{N} Z_i \,, \tag{32}$$

which appears here the first time and, as we shall see, it will emerge in some form or other again and again in the area of variable sampling.

Let us now discuss the other extreme case, namely the minimum sample size $n = 1$. In this case the detection probability $1 - \beta(C; \mu_1, \ldots, \mu_n)$ is given by

$$1 - \beta(C; \mu_1, \ldots, \mu_N) = \mathbb{P}_{H_1}(Z \in C) = \frac{1}{N} \int_{z \in C} \frac{1}{\sqrt{2\pi}\sigma} \sum_{i=1}^{N} \exp\left(- \frac{(z - \mu_i)^2}{2\,\sigma^2} \right) dz \,. \tag{33}$$

In case of the *minimum* sample size $n = 1$, the game theoretical solution is given in

THEOREM 5 (see [18])

Let the inspector's strategy set Δ_α be the set of all test procedures with a given false alarm probability α, let the operator's strategy set be given by (28) and let the payoff to the inspector be the detection probability given by (33). The game theoretical solution of the zero-sum game $\left(\Delta_\alpha, Y_\mu, 1 - \beta(C; \mu_1, \ldots, \mu_N)\right)$ is given as follows: Let $\mu^*(N)$ be the unique zero point of the function $F(\mu)$, defined by

$$F(\mu) := \Phi\left(U(1-\alpha) - \frac{1}{N}\frac{\mu}{\sigma}\right) - \frac{1}{N}\Phi\left(U(1-\alpha) - \frac{\mu}{\sigma}\right) - \left(1 - \frac{1}{N}\right)(1-\alpha) \,,$$

where $\Phi(\cdot)$ is the distribution function of a standard normally distributed random variable. An optimal strategy for the inspector is the test given by the critical region

$$C^* := \{Z : Z > \sigma\, U(1-\alpha)\} \,, \tag{34}$$

which is independent of the strategy of the operator. For $\mu \leq \mu^*(N)$ an optimal strategy of the operator is the uniform falsification

$$\mu_i^* = \frac{\mu}{N}, \quad i = 1, \ldots, N \,,$$

whereas for $\mu \geq \mu^*(N)$ it is

$$\boldsymbol{\mu}^* := (\mu_1^*, \ldots, \mu_N^*) \in \{\, (\mu, 0, \ldots, 0), (0, \mu, 0, \ldots, 0), \ldots, (0, \ldots, 0, \mu) \,\}.$$

The optimal detection probability $1 - \beta^*$ is

$$1-\beta^{*}=\begin{cases}\Phi\left(\frac{1}{N}\frac{\mu}{\sigma}-U(1-\alpha)\right) \\ \frac{1}{N}\Phi\left(\frac{\mu}{\sigma}-U(1-\alpha)\right)+\left(1-\frac{1}{N}\right)\alpha\end{cases}\quad \text{for}\quad \begin{matrix}\mu\le\mu^{*}(N)\\ \mu\ge\mu^{*}(N)\end{matrix}. \tag{35}$$

The sequence $\{\mu^{*}(N)\}$ of critical falsifications is strictly monotonically increasing in N; it starts with $\mu^{*}(2)=2\,\sigma\,U(1-\alpha)$ and converges to a limiting value μ^{*} which is implicitly given by

$$\frac{\mu^{*}}{\sigma}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\left(U(1-\alpha)\right)^{2}}{2}\right)+\Phi\left(U(1-\alpha)-\frac{\mu^{*}}{\sigma}\right)-1+\alpha=0.$$

This result, which appears in some form or other again and again in this problem area, has an intuitive interpretation: If the total falsification is small, then from a falsification point of view it is best to distribute it on all N data, since it is hoped that the measurement uncertainty covers this falsification. If on the other hand, the total falsification is large, it cannot be covered by the measurement uncertainty, thus, the number of falsified data has to be as small as possible in order that the probability that the falsified datum is verified is as small as possible.

A word on wording: $1-\beta^{*}$ as given by (35) is the optimal probability that the observed difference z falls into the critical region (34) of the test. This may happen if a falsified or a non-falsified datum (and therefore: a difference) is selected; in the latter case a false alarm is raised. Thus, it depends on the so-called *second action level* whether we can call $1-\beta^{*}$ the probability of detection: If after an alarm *only* the tested difference is tested again by using a second inspector measurement on the same datum – this time with a very precise technique – then it may happen that a falsification is not detected. If, however, after an alarm *all* differences are tested, then the falsification will be detected. For these reasons, and if no second action level procedure is agreed upon, it has been suggested to call $1-\beta^{*}$ the optimal alarm probability; see [17].

Further results for intermediate sample sizes, i.e., $1<n<N$, have been obtained for very small and for very large total falsifications μ: Whereas in the former case again the D-statistic is optimal, in the latter case the problem turns into an attribute sampling one which means that the single differences $Z_i\, i=1,\dots,n$ evaluated separately. Analytical solutions for given values of σ, n and μ are not feasible as an examination of the case $N=3$ and $n=2$, the simplest one not covered by Theorems 4 and 5, indicates, see, e.g., [19]. We will return to this issue in section 4.1.

3.2 One Class of Material: Two Measurement Devices

Let us return to the procedure treated in section 2.2 and let us assume now that measurement errors cannot be ignored. For demonstration we consider N data and the *maximum* sample size case $n=N$. Furthermore, we assume – and this is common knowledge to the operator – that the first $N-1$ data are verified with a device with variance $\sigma^{2}=1$, and the last one with a more accurate device with variance $\sigma^{2}<1$.

Since this game theoretical model as well as its solution are presented here the first time, we derive the solution. Moreover, we do not formulate it in form of a Theorem, in order to demonstrate the way in which solutions of this kind are obtained.

The joint density functions of $(Z_1, \dots, Z_N)$ under H_0 and H_1 are given by

$$f_0(z_1, \dots, z_N) := \frac{1}{\left(\sqrt{2\pi}\right)^{N-1}} \exp\left(-\frac{1}{2}\sum_{i=1}^{N-1} {z_i}^2\right) \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{{z_N}^2}{2\,\sigma^2}\right) \tag{36}$$

and

$$f_1(z_1, \dots, z_N) := \frac{1}{\left(\sqrt{2\pi}\right)^{N-1}} \exp\left(-\frac{1}{2}\sum_{i=1}^{N-1} \left(z_i - \mu_i\right)^2\right) \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\left(z_N - \mu_N\right)^2}{2\,\sigma^2}\right). \tag{37}$$

In this case the Neyman-Pearson Lemma, see, e.g., [10], leads with (36) and (37) to the critical region

$$C^* := \left\{(z_1, \dots, z_N) : \frac{f_1(z_1, \dots, z_N)}{f_0(z_1, \dots, z_N)} > k\right\} = \left\{(z_1, \dots, z_N) : \sum_{i=1}^{N-1} \mu_i\, z_i + \frac{\mu_N\, z_N}{\sigma^2} > k'\right\}$$

with two constants $k, k' \in [0, \infty)$, and thus to the test statistic

$$D := \sum_{i=1}^{N-1} \mu_i\, Z_i + \frac{\mu_N\, Z_N}{\sigma^2}. \tag{38}$$

For a given false alarm probability α we get for the constant k'

$$\mathbb{P}_{H_0}\left((Z_1, \dots, Z_N) \in C^*\right) = \mathbb{P}_{H_0}(D > k') = 1 - \Phi\left(\frac{k'}{\sqrt{\sum_{i=1}^{N-1} \mu_i^2 + \frac{\mu_N^2}{\sigma^2}}}\right) = \alpha,$$

i.e., k' is explicitly given by

$$k' = U(1-\alpha)\sqrt{\sum_{i=1}^{N-1} \mu_i^2 + \frac{\mu_N^2}{\sigma^2}}\,. \tag{39}$$

Therefore, the detection probability $1 - \beta(C^*; \mu_1, \dots, \mu_N) := \mathbb{P}_{H_1}\left((Z_1, \dots, Z_N) \in C^*\right) = \mathbb{P}_{H_1}(D > k')$ is for *any* falsification $(\mu_1, \dots, \mu_N) \in Y_\mu$, see (28), given by

$$1 - \beta(C^*; \mu_1, \dots, \mu_N) = \Phi\left(\sqrt{\sum_{i=1}^{N-1} \mu_i^2 + \frac{\mu_N^2}{\sigma^2}} - U(1-\alpha)\right). \tag{40}$$

The right-hand side of (40) has a global minimum at

$$\mu_1^* = \mu_2^* = \cdots = \mu_{N-1}^* = \frac{\mu}{N-1+\sigma^2} \quad \text{and} \quad \mu_N^* = \frac{\mu\,\sigma^2}{N-1+\sigma^2}$$

because we have for any $(\mu_1, \ldots, \mu_N) \in Y_\mu$

$$\sum_{i=1}^{N-1} \mu_i^2 + \frac{\mu_N^2}{\sigma^2} = \sum_{i=1}^{N-1} \left(\mu_i - \frac{\mu}{N-1+\sigma^2}\right)^2 + \frac{1}{\sigma^2}\left(\mu_N - \frac{\mu\,\sigma^2}{N-1+\sigma^2}\right)^2 + \frac{\mu^2}{N-1+\sigma^2}\,.$$

Thus, the optimal detection probability is given by

$$1-\beta^* = \Phi\left(\frac{\mu}{\sqrt{N-1+\sigma^2}} - U(1-\alpha)\right) \tag{41}$$

and the optimal test statistic together with the threshold k^*, using (38) and (39), by

$$D^* = \sum_{i=1}^{N} Z_i \quad \text{and} \quad k^* = U(1-\alpha)\sqrt{N-1+\sigma^2}\,.$$

For the sake of completeness, we mention that it can be shown that the optimal detection probability (41) is also obtained if the order of the inspector's and operator's optimization of their respective strategies is reversed.

At first sight this result is very surprising. Even though $\mu_N^* < \mu_i^*$ for $i = 1, \ldots, N-1$ was to be expected, the simple form of D^* was not. It may be explained by the fact that the operator is assumed to know which datum is verified with the precise method thus, he adjusts his optimal falsification of this datum such that all data appear to be drawn from the same ensemble, recall Theorem 4. We have obtained similar properties of optimal strategies in earlier sections.

Another interesting feature of this solution is that, as long as the operator knows which datum is verified with the precise method, the result is independent of its number. Nevertheless, this assumption may be considered somehow unrealistic. It sheds, however, new light on the use of the D-statistic, in other words, it may serve as another justification of this statistic. Models without this assumption are considered in [20] and [21], and they lead to different results.

3.3 Several Classes of Material

As in section 2.3 let us assume that there are K classes of material, and that the i-th class contains N_i batches, the data X_{ij} of which are reported to an inspector. We write this as an additive error model

$$X_{ij} = \mu_{ij} + E_{Oij} + F_{Oi}, \qquad i = 1, \ldots, K, j = 1, \ldots, N_i$$

where μ_{ij} is the true value of the j-th datum in the i-th class, E_{Oij} is the random and F_{Oi} the (short term) systematic error, which is assumed to have the same value for all data $j = 1, \ldots, N_i$ in the i-th class. The errors are assumed to be independently and normally distributed with zero expectation and known variances,

$$\begin{aligned} &\mathbb{E}(E_{Oij}) = \mathbb{E}(F_{Oi}) = 0 \\ &\mathbb{V}(E_{Oij}) = \sigma_{Ori}^2, \qquad \mathbb{V}(F_{Oi}) = \sigma_{Osi}^2 \end{aligned} \qquad \text{for} \quad i = 1, \ldots, K, j = 1, \ldots, N_i\,.$$

The inspector verifies n_i of the N_i batch data in the i-th class with the help of independent measurements. The inspector's findings can be written as

$$Y_{ij} = \mu_{ij} + E_{Iij} + F_{Ii}, \qquad i = 1, \dots, K, j = 1, \dots, n_i \,, \tag{42}$$

where the random errors E_{Iij} and the (short term) systematic errors F_{Ii} are again independently and normally distributed with zero expectation and known variances:

$$\begin{aligned} &\mathbb{E}(E_{Iij}) = \mathbb{E}(F_{Ii}) = 0 \\ &\mathbb{V}(E_{Iij}) = \sigma_{Iri}^2, \qquad \mathbb{V}(F_{Ii}) = \sigma_{Isi}^2 \end{aligned} \qquad \text{for} \quad i = 1, \dots, K, j = 1, \dots, n_i \,.$$

Note that in (42) we have assumed that the first n_i items are verified by the inspector. This assumption can be made because first the analysis relies of the differences $X_{ij} - Y_{ij}$ in which the true value cancels out, see below, and second in model A all data are falsified by the same amount, see Definition 4.

Again, since the inspector is not interested in the true values of the X_{ij} and Y_{ij}, but only in the deviations between corresponding reported and independently measured data, he will construct his test procedure with the help of the differences between these data:

DEFINITION 3 (see [12])

The differences

$$Z_{ij} = X_{ij} - Y_{ij}, \qquad i = 1, \dots, K, j = 1, \dots, n_i \,,$$

between the operator's reported data X_{ij} and the independent observations Y_{ij} of the inspector are, under the null hypothesis H_0 (no falsification), assumed to be normally distributed with expectation

$$\mathbb{E}_{H_0}(Z_{ij}) = 0$$

and with variances and covariances

$$\begin{aligned} \mathbb{V}_{H_0}(Z_{ij}) &= \sigma_{ri}^2 + \sigma_{si}^2 = \sigma_{0ri}^2 + \sigma_{0ri}^2 + \sigma_{0si}^2 + \sigma_{Isi}^2 \\ cov(Z_{ij}, Z_{i'j'}) &= \begin{cases} 0 & for \quad i \neq i' \\ \sigma_{si}^2 & \quad\;\; i = i', j \neq j' \end{cases} . \end{aligned} \tag{43}$$

As in the attribute sampling case, we define ε_i to be the effort of the inspector for verifying one datum in the i-th class, and we assume that the inspector has the total inspection effort ε at his disposal in order to verify n_i data in the i-th class. Again, we have to make assumptions in which way the operator will – if at all – falsify the reported data.

DEFINITION 4 (see [12])

We call *model A* that set of falsification strategies which contains all possibilities of the operator to falsify *all* N_i data of the i-th class by the *same* amount $\mu_i \leq \mu_{i,max}, i = 1, \dots, K$, which means

$$\mathbb{E}_{H_1}(Z_{ij}) = \mu_i \quad for \;\; i = 1, \dots, K, j = 1, \dots, n_i \,,$$

and which is supposed to be known to the inspector, such that the data are falsified by the total amount μ of material, i.e., the operator's strategy set is given by

$$Y_\mu := \left\{ (\mu_1, \ldots, \mu_K) \in \mathbb{R}_+^K : \sum_{i=1}^{K} \mu_i N_i = \mu \right\}. \tag{44}$$

One possible interpretation of this model is that in case of intended falsification, the operator changes the calibration of those instruments which are used for the determination of the material contents of the batches in the K classes. Analytically, this model does not only permit a complete solution, but also provides a justification of the D-statistic for several classes of material.

If the sample sizes $(n_1, \ldots, n_K)$ are assumed to be continuous variables, then the game theoretical solution for model A is given in

THEOREM 6 (see [14])

Let the inspector's strategy set $\Delta_\alpha \otimes X_\varepsilon$ consists of all test procedures with a given false alarm probability α testing the two hypotheses H_0 and H_1 for the random variables Z_{ij} (see Definitions 3 and 4) together with sample sizes $(n_1, \ldots, n_K)$ from the set X_ε, given by (14), let the operator's strategy set be given by (44), and let the payoff to the inspector be the detection probability $1 - \beta_A$. The game theoretical solution of the zero-sum game $(\Delta_\alpha, Y_\mu, 1 - \beta_A)$ is given as follows: An optimal strategy for the inspector is given by

$$n_i^* = \frac{\varepsilon}{\sum_{j=1}^{K} N_j \, \sigma_{rj} \sqrt{\varepsilon_j}} \frac{N_i \, \sigma_{ri}}{\sqrt{\varepsilon_i}}, \quad i = 1, .., K, \tag{45}$$

and an optimal strategy of the operator by

$$\mu_i^* = \frac{\mu}{\sigma^{*2}} \left(\frac{1}{\varepsilon} \left(\sum_{j=1}^{K} N_j \, \sigma_{rj} \sqrt{\varepsilon_j} \right) \sigma_{ri} \sqrt{\varepsilon_i} + N_i \, \sigma_{si}^2 \right), \quad i = 1, \ldots, K,$$

where σ^{*2} is given by

$$\sigma^{*2} = \frac{1}{\varepsilon} \left(\sum_{j=1}^{K} N_j \, \sigma_{rj} \sqrt{\varepsilon_j} \right)^2 + \sum_{j=1}^{K} N_j^2 \, \sigma_{sj}^2 . \tag{46}$$

The optimal detection probability $1 - \beta^*$ is

$$1 - \beta_A^* = \Phi \left(\frac{\mu}{\sqrt{\sigma^{*2}}} - U(1 - \alpha) \right).$$

Note that if $n_i^*, i = 1, \ldots, K$, according to (45) are integers, then σ^{*2} given by (46) can be interpreted as the variance of the D-statistic for K classes of material:

$$D^* := \sum_{i=1}^{K} \frac{N_i}{n_i} \sum_{j=1}^{n_i} Z_{ij} \,, \tag{47}$$

because (43) implies for any $n_i = 1, \dots, N_i$

$$\mathbb{V}_{H_1}\left(\sum_{j=1}^{n_i} Z_{ij}\right) = n_i\,(\sigma_{ri}^2 + \sigma_{si}^2) + 2\,\frac{n_i(n_i-1)}{2}\,\sigma_{si}^2 = n_i\,\sigma_{ri}^2 + n_i^2\,\sigma_{si}^2$$

and therewith

$$\mathbb{V}_{H_1}(D^*) = \sum_{i=1}^{K} \left(\frac{N_i}{n_i}\right)^2 \mathbb{V}_{H_1}\left(\sum_{j=1}^{n_i} Z_{ij}\right) = \sum_{i=1}^{K} \left(\frac{N_i}{n_i}\right)^2 \left(n_i\,\sigma_{ri}^2 + n_i^2\,\sigma_{si}^2\right) = \sum_{i=1}^{K} \frac{N_i^2}{n_i}\sigma_{ri}^2 + \sum_{i=1}^{K} N_i^2\,\sigma_{si}^2 \,. \tag{48}$$

Thus, if n_i^* from (45) are integers, we get, using (48),

$$\mathbb{V}_{H_1}(D^*) = \sum_{i=1}^{K} \frac{N_i^2}{n_i}\sigma_{ri}^2 + \sum_{i=1}^{K} N_i^2\,\sigma_{si}^2 = \frac{1}{\varepsilon}\left(\sum_{i=1}^{K} N_i\,\sqrt{\varepsilon_i}\,\sigma_{ri}\right)^2 + \sum_{i=1}^{K} N_i^2\,\sigma_{si}^2 = \sigma^{*2} \,,$$

i.e., (46). The D-statistic for K classes of material, as given by (47), was proposed the first time in 1971, see [22], for use in nuclear material safeguards. At that time, it was justified by heuristic arguments. Theorem 6 shows under which conditions it can be derived from first statistical principles. In fact, we would have obtained the sampling distribution (45) if we would had minimized the variance of the D-statistic given by (48) with respect to the $n_1, \dots, n_K$ under the boundary condition (14).

If all systematic errors vanish, i.e., $\sigma_{si}^2 = 0$ for $i = 1, \dots, K$, and all class specific efforts are equal, i.e., $\varepsilon_i = \varepsilon_1$ for $i = 2, \dots, K$, then with

$$n := \sum_{i=1}^{K} n_i = \frac{\varepsilon}{\varepsilon_1} \,, \quad N := \sum_{i=1}^{K} N_i, \quad \sigma_r := \frac{1}{N}\sum_{i=1}^{K} N_i\,\sigma_{ri}$$

we obtain from Theorem 6 for $i = 1, \dots, K$

$$n_i^* = \frac{n}{N\,\sigma_r}\,N_i\,\sigma_{ri} \,, \quad \sigma^{*2} = \frac{N^2\,\sigma_r^2}{n}, \quad \mu_i^* = \frac{\mu}{N\,\sigma_r}\sigma_{ri}, \quad 1 - \beta_A^* = \Phi\left(\frac{\sqrt{n}}{\sigma_r}\frac{\mu}{N} - U(1-\alpha)\right).$$

The optimal detection probability is thus calculated as if all K classes were aggregated into a simple class of N items, all of which are falsified by the same amount μ/N and n of which are verified. We saw the same in Theorems 2 and 3 and recognize it now to be a general feature of optimal stratified sampling strategies.

Let us consider *model B*, given by Definition 1. Since it is not possible to determine the optimal test procedure for this model, we use the D-statistic (47). However, since we still have problems in view of its complicated distribution function, we use a normal distribution *approximation*:

$$D \sim \begin{cases} \mathcal{N}\left(0, \mathbb{V}_{H_0}(D)\right) \\ \mathcal{N}\left(\mu, \mathbb{V}_{H_1}(D)\right) \end{cases} \text{for} \quad \begin{matrix} H_0 \\ H_1 \end{matrix}$$

with the variances given by

$$\mathbb{V}_{H_0}(D) = \sum_{i=1}^{K} N_i^2 \left(\frac{\sigma_{ri}^2}{n_i} + \sigma_{si}^2\right) \quad \text{and} \quad \mathbb{V}_{H_1}(D) = \mathbb{V}_{H_0}(D) + \sum_{i=1}^{K} \left(\mu_i^2 \, r_i \, (N_i - r_i) + N_i^2 \, \sigma_{si}^2\right) \tag{49}$$

for the sampling with replacement scheme. Then the detection probability is given by

$$1 - \beta_B = \Phi\left(\frac{\mu - \sqrt{\mathbb{V}_{H_0}(D)} \, U(1-\alpha)}{\sqrt{\mathbb{V}_{H_1}(D)}}\right). \tag{50}$$

If we consider the special case

$$\mu \gg \sqrt{\mathbb{V}_{H_0}(D)} \; U(1-\alpha)$$

then (50) simplifies to

$$1 - \beta_B \approx \Phi\left(\frac{\mu}{\sqrt{\mathbb{V}_{H_1}(D)}}\right), \tag{51}$$

thus, we can use the variance $\mathbb{V}_{H_1}(D)$ as optimization criterion.

If the sample sizes $(n_1, \dots, n_K)$ and the number of falsified items $(r_1, \dots, r_K)$ can be considered as continuous variables, then the game theoretical solution is given in

THEOREM 7 (see [14])

Let the inspector's strategy set by given by X_ε and the operator's strategy set by

$$Y_\mu := \left\{(r_1, \dots, r_K, \mu_1, \dots, \mu_K) \in \mathbb{R}_+^{2K} : \sum_{i=1}^{K} \mu_i r_i = \mu\right\}$$

and let the payoff to the inspector be the detection probability $1 - \beta_B$ given by (51). The game theoretical solution of the zero-sum game $\left(X_\varepsilon, Y_\mu, 1 - \beta_B\right)$ resp. $\left(X_\varepsilon, Y_\mu, -\mathbb{V}_{H_1}(D)\right)$ is given as follows: If

$$\frac{1}{2} \sum_{i=1}^{K} N_i \, \mu_{i,max} - \mu \geq 0 \quad \text{and} \quad \mu_{i,max} \geq \frac{2 \, \sigma_{ri}}{\sqrt{\chi \, \epsilon_i}} \;, i = 1, \dots, K$$

(χ defined below) then an optimal strategy for the inspector is given by

$$n_i^* = \frac{\varepsilon}{\sum_{j=1}^{K} N_j\, \varepsilon_j\, S_j}\, N_i\, S_i\,, \quad i = 1,..,K, \tag{52}$$

and an optimal strategy of the operator by

$$r_i^* = \frac{N_i}{2}\left(1 - \frac{2}{\mu_{i,max}}\, S_i\right) \quad \text{and} \quad \mu_i^* = \mu_{i,max}\,, \quad i = 1,\dots,K\,, \tag{53}$$

where S_i is defined by

$$S_i^2 = \frac{\sigma_{ri}^2 + \left(\mu_{i,max}\right)^2/4}{1 + \chi\, \varepsilon_i}, \quad i = 1,\dots,K, \tag{54}$$

and where χ is uniquely determined by

$$\sum_{j=1}^{K} N_j\, S_j = \frac{1}{2}\sum_{j=1}^{K} N_j\, \mu_{j,max} - \mu, \tag{55}$$

The optimal variance $\mathbb{V}_{H_1}^*(D)$ is given by

$$\mathbb{V}_{H_1}^*(D) = \frac{\chi}{\varepsilon}\left(\sum_{j=1}^{K} N_j\, S_j\, \varepsilon_j\right)^2 + \sum_{j=1}^{K} N_j^2\, \sigma_{sj}^2\,.$$

If the total falsification μ is half the maximum falsification, we get from (55)

$$\sum_{j=1}^{K} N_j\, S_j = 0$$

which implies $S_1 = \cdots = S_K = 0$, and thus by (54) $\chi \to \infty$. Therefore, (54) yields

$$\lim_{\chi\to\infty}\left(\frac{S_j}{S_i}\right)^2 = \frac{\sigma_{rj}^2 + \left(\mu_{j,max}\right)^2/4}{\sigma_{ri}^2 + \left(\mu_{i,max}\right)^2/4}\,\frac{\varepsilon_i}{\varepsilon_j},$$

and the optimal strategies (52) and (53) are, for any $i = 1,..,K$, explicitly given by

$$n_i^* = \frac{\varepsilon}{\sum_{j=1}^{K} N_j \sqrt{\varepsilon_j\left(\sigma_{rj}^2 + \left(\mu_{j,max}\right)^2/4\right)}}\, N_i \sqrt{\frac{\sigma_{ri}^2 + \left(\mu_{i,max}\right)^2/4}{\varepsilon_i}} \quad \text{and} \quad r_i^* = \frac{N_i}{2}\,,$$

and furthermore

$$\mathbb{V}^*_{H_1}(D) = \frac{1}{\varepsilon}\left(\sum_{j=1}^{K} N_j \sqrt{\varepsilon_j \left(\sigma_{rj}^2 + \left(\mu_{j,max}\right)^2/4\right)}\right)^2 + \sum_{j=1}^{K} N_j^2\, \sigma_{sj}^2 \ .$$

Comparing this variance with that given by (46) we see that it is larger and therefore, leads to a smaller detection probability. On the other hand if we take μ to be close to zero, then the variance $\mathbb{V}^*_{H_1}(D)$ approaches the variance $\mathbb{V}_{H_0}(D)$ (see (49)), and we get from (51)

$$1 - \beta_B \approx \Phi\left(\frac{\mu}{\sqrt{\mathbb{V}_{H_0}(D)}}\right)$$

thus, the optimal class sample sizes of the inspector are determined such that the variance of the D -statistic under H_0 is minimized. This however, as mentioned leads to the sampling distribution (45) as given by Theorem 6.

These results provide a qualitative answer to the question as to which model is appropriate for the inspector, who does not know if the operator will choose the strategy underlying Theorem 6 or that of Theorem 7. If the inspector thinks that the size of the falsification, relative to the standard deviation $\sqrt{\mathbb{V}^*_{H_1}(D)}$, is small, he can assume an uniformly distributed falsification and apply the sampling procedure of Theorem 6. Otherwise he should act according to Theorem 7.

4. Variable Sampling in the Attribute Mode and in the Variable Mode

Variables inspection presupposes the existence of a variable measuring instrument or a variable tester; see [23]. Unlike attributes inspection, it is necessary to have in mind the specific tester to be used in each stratum at the planning stage, because the measurement error variances affect the planning. Now, variables inspection can also be used in the *attribute mode*, if the falsification is sufficiently small to escape detection with the attribute tester. In other words, a variable tester can be used in order to only make a qualitative statement. Naturally, one can determine the efficiency of such a procedure if the statistical properties of this tester are known. In the following considerations systematic measurement errors will be ignored.

4.1 One Class of Material

In section 3.1 we mentioned that in case of $N \geq 2$ reported and $n > 1$ verified data, only for the very special case $n = N$ an optimal test is known. Therefore, for general N and n heuristic test procedures have been developed which may be considered extensions of the tests given by Theorems 4 and 5: On the one hand and in line with Theorem 4, the n differences between reported and verified data are added, and this sum is used as test statistic. This procedure is called *variable sampling in the variable mode*. On the other hand, and in line with Theorem 5, all differences are tested separately. This procedure is called *variable sampling in the attribute mode*.

Let us consider the first procedure. Here, the D-statistic is used for data evaluation. According to (32) and for $N = n$ the value of the D-statistic is compared with the threshold $k = \sqrt{n}\,\sigma\, U(1-\alpha)$ and we get, recalling that we exclude systematic errors,

$$\mathbb{P}_{H_0}\left(D > \sqrt{n}\,\sigma\,U(1-\alpha)\right) = 1 - \mathbb{P}_{H_0}\left(\frac{D}{\sqrt{n}\,\sigma} \le U(1-\alpha)\right) = 1 - \Phi\big(U(1-\alpha)\big) = \alpha\,.$$

If there are ℓ falsified data in the sample, and if each falsified datum is falsified by the amount μ', then the expected value and the variance of the D-statistic are

$$\mathbb{E}_{H_1}(D) = \mathbb{E}_{H_1}\left(\sum_{i=1}^{n} Z_i\right) = \ell\mu' \quad \text{and} \quad \mathbb{V}_{H_1}(D) = \sum_{i=1}^{n} \mathbb{V}_{H_1}(Z_i) = n\,\sigma^2\,,$$

and therefore, the non-identification probability, see [17], is given by

$$\mathbb{P}_{H_1}(D \le k) = \mathbb{P}_{H_1}\left(\frac{D - \ell\mu'}{\sqrt{n}\,\sigma} \le \frac{k - \ell\mu'}{\sqrt{n}\,\sigma}\right) = \Phi\left(U(1-\alpha) - \frac{\ell\,\mu'}{\sqrt{n}\,\sigma}\right)\,. \tag{56}$$

Furthermore, if the so-called equal diversion hypothesis, see [17], is assumed, i.e., if in total under the N data r data are falsified by the amount $\mu = \mu'\,r$, then (56) yields

$$\Phi\left(U(1-\alpha) - \frac{\ell}{r}\frac{\mu}{\sqrt{n}\,\sigma}\right)\,.$$

Thus, the overall detection probability is, using the selection probability given by the hypergeometric distribution, see section 2.1, according to the law of total probability

$$1 - \beta_{var}(n,r) := 1 - \sum_{\ell=max\left(0,r-(N-n)\right)}^{min(r,n)} \Phi\left(U(1-\alpha) - \frac{\ell}{r}\frac{\mu}{\sqrt{n}\,\sigma}\right) \frac{\binom{r}{\ell}\binom{N-r}{n-\ell}}{\binom{N}{n}}, \tag{57}$$

which simplifies for $r = 1$ and $r = N$ to

$$1 - \beta_{var}(n,r) = \begin{cases} 1 - \Phi\left(U(1-\alpha) - \dfrac{\sqrt{n}}{N}\dfrac{\mu}{\sigma}\right) \\ 1 - \left((1-\alpha)\left(1 - \dfrac{n}{N}\right) + \Phi\left(U(1-\alpha) - \dfrac{\mu}{\sqrt{n}\,\sigma}\right)\dfrac{n}{N}\right) \end{cases} \quad \text{for} \quad \begin{matrix} r = N \\ r = 1 \end{matrix}\,.$$

While for $n = N$, i.e., the maximum sample size case, both expressions reduce to (31), for $n = 1$, i.e. the minimum sample size case, these expressions simplify to (35).

According to the second procedure where – as mentioned – all n differences are tested individually with a false alarm probability α', i.e. the threshold for each individual test is set to $\sigma\,U(1-\alpha')$, because we have for any $i = 1, \ldots, n$

$$\mathbb{P}_{H_0}\big(Z_i > \sigma\,U(1-\alpha')\big) = 1 - \mathbb{P}_{H_0}\left(\frac{Z_i}{\sigma} < U(1-\alpha')\right) = 1 - \Phi\big(U(1-\alpha')\big) = \alpha'\,.$$

Now, if one datum is tested, the probability that its difference is significant, i.e., falls into the critical region $\{z: z > \sigma\,U(1-\alpha')\}$ of the test, is under the same operator behavior as before, i.e., $\mathbb{E}_{H_1}(Z_i) = \mu/r$ and $\mathbb{V}_{H_1}(D) = \sigma^2$, given by

$$\begin{cases} \mathbb{P}_{H_1}\left(Z_i > \sigma\, U(1-\alpha')\right) = 1 - \Phi\left(U(1-\alpha') - \dfrac{1}{r}\dfrac{\mu}{\sigma}\right) & \text{if the datum is falsified} \\ \alpha' & \text{if the datum is not falsified} \end{cases} .$$

Because we exclude systematic errors, the total false alarm probability α and the individual false alarm probability α' fulfil the relation

$$\alpha := \mathbb{P}_{H_0}(at\ least\ one\ false\ alarm) = 1 - \mathbb{P}_{H_0}(no\ false\ alarm) = 1 - (1-\alpha')^n . \quad (58)$$

Thus, again according to the law of total probability, the detection probability is given by

$$1 - \sum_{\ell=max(0,r-(N-n))}^{min(r,n)} \left(\Phi\left(U(1-\alpha') - \frac{1}{r}\frac{\mu}{\sigma}\right)\right)^{\ell} (1-\alpha')^{n-\ell} \frac{\binom{r}{\ell}\binom{N-r}{n-\ell}}{\binom{N}{n}} ,$$

and therefore, using (58), is given by

$$\begin{aligned} & 1 - \beta_{att}(n,r) \\ & = 1 - \sum_{\ell=max(0,r-(N-n))}^{min(r,n)} \left(\Phi\left(U\left(\sqrt[n]{1-\alpha}\right) - \frac{1}{r}\frac{\mu}{\sigma}\right)\right)^{\ell} (1-\alpha)^{1-\frac{\ell}{n}} \frac{\binom{r}{\ell}\binom{N-r}{n-\ell}}{\binom{N}{n}} . \end{aligned} \quad (59)$$

Of course, (31) and (34) are special cases of (57) and (59). As regards to the wording "detection probability" the same holds here as what has been said after Theorem 5, i.e., $1 - \beta_{att}(n,r)$ should be better called alarm probability.

Note that IAEA sampling plans rely on the assumption that an observed significant difference is clarified with certainty, which means that with some (perfect) method, which is not modelled in the sampling plan methodology, it is known without committing any error that a significant difference is only due to measurement errors, i.e., H_0 is true, or is due to a diversion, i.e., H_1 is true; see [17]. It can be shown that under this additional assumption the detection/alarm probability (59) has to be modified, and is given by

$$1 - \sum_{\ell=max(0,r-(N-n))}^{min(r,n)} \left(\Phi\left(U\left(\sqrt[n]{1-\alpha}\right) - \frac{1}{r}\frac{\mu}{\sigma}\right)\right)^{\ell} \frac{\binom{r}{\ell}\binom{N-r}{n-\ell}}{\binom{N}{n}} .$$

The question arises as to which values of r should be assumed to be chosen by the operator for given values of the total falsification μ, and which of the two test procedures should be applied. Numerical calculations as well as the optimal tests for $N = 3$ and $n = 2$ indicate that, see [19],

- For large total falsification μ the attribute mode testing with as small as possible number of falsifications, and
- For small total falsification μ the variable mode testing with largest possible number of falsifications, eventually $r = N$

should be used. These are very general statements. It remains to develop an idea, at best some rule of thumb, which indicates for which set of parameters N, n, μ/σ and α which test procedure should be utilized if one assumes that only the two test procedures introduced above are available.

4.2 Several Classes of Material

Just to give an idea what still can be achieved, we consider model A as given by Definition 4 and assume furthermore, that the total number of verified data n is fixed, i.e., the inspector's strategy set is given by

$$X_n := \left\{ (n_1, \dots, n_K) \in \mathbb{R}_+^K : \sum_{i=1}^{K} n_i = n \right\}. \tag{60}$$

The operator's strategy set is Y_μ as given by (44). If each stratum has N_i data ($i = 1, \dots, K$) and σ_i the stratum specific measurement uncertainties, then the overall detection probability is, for any $\boldsymbol{n} := (n_1, \dots, n_K) \in X_n$ and any $\boldsymbol{\mu} := (\mu_1, \dots, \mu_K) \in Y_\mu$, given by

$$1 - \beta(\boldsymbol{n}, \boldsymbol{\mu}) := 1 - \prod_{i=1}^{K} \left(\Phi\left(U\left(\sqrt[n]{1-\alpha}\right) - \frac{\mu_i}{\sigma_i} \right) \right)^{n_i}. \tag{61}$$

Note that the system parameters N_i, σ_i, α, μ and n are known both to the inspector and the operator.

If the sample sizes $(n_1, \dots, n_K)$ can be considered as continuous variables, then the game theoretical solution is given in

THEOREM 8 (see [12])

Let the inspector's and operator's strategy sets be given by (60) and (44), and let the payoff to the inspector be the detection probability given by (61). The game theoretical solution of the zero-sum game $\left(X_n, Y_\mu, 1 - \beta(\boldsymbol{n}, \boldsymbol{\mu})\right)$ is given as follows: Optimal strategies for the inspector and for the operator are, for any $i = 1, \dots, K$, given by

$$n_i^* = \frac{n}{\sum_{j=1}^{K} N_j \, \sigma_j} N_i \, \sigma_i \quad \text{and} \quad \mu_i^* = \frac{\mu}{\sum_{j=1}^{K} N_j \, \sigma_j} \sigma_i \ . \tag{62}$$

The optimal detection probability $1 - \beta^*$ is given by

$$1 - \beta^* = 1 - \left(\Phi\left(U\left(\sqrt[n]{1-\alpha}\right) - \frac{\mu}{\sum_{j=1}^{K} N_j \, \sigma_j} \right) \right)^n .$$

The most interesting aspect of this solution is that the optimal sample size distribution (62) of the inspector is exactly the same as that given by (45) of Theorem 6 for $\varepsilon_i = \varepsilon$ for $i = 1, \dots, K$. If

$$N := \sum_{i=1}^{K} N_i, \quad \bar{\mu} := \frac{\mu}{N}, \quad \bar{\sigma} := \frac{1}{N} \sum_{i=1}^{K} N_i \, \sigma_i \ ,$$

then the optimal detection probability $1 - \beta^*$ is again the same as the one which one would have obtained if one considered all K classes as one single class out of which n data were verified and all of which were falsified by the amount $\bar{\mu}$, with standard deviation $\bar{\sigma}$ of one a single inspector-operator measurement difference. One gets similar results, as we saw, as special cases from the Theorems given above.

5. Concluding Remarks

So far, we have only considered non-sequential data verification problems: At a given point of time a set of data is reported by an operator, and an inspector verifies a part of these data with the help of independent measurements. This situation is typical for inventory verification problems, when the plant under consideration is shut down and there is enough time for an inspector to draw his samples.

There are some specific flow measurement data verification problems where the techniques described in the foregoing section can be applied as well: If one single flow measurement datum consists, among other things, of a concentration measurement which is performed by first drawing a sample and then analyzing its concentration and if such a sample can be stored for some time, then one has again a non-sequential decision problem. The verification of volume data, on the other hand, is only possible as long as the volume has not yet disappeared in the production process. Therefore, this verification problem is of a truly sequential nature.

Under very simplifying assumptions, e.g., if there is only one falsification in a sequence of n events, an analytical treatment is still possible; see [14]. If one assumes, however, that more than one falsification may be intended, then one has to deal with sequential games *without recursive structure* and analysis becomes very difficult: Sequential data verification, especially in the variable sampling mode, remains one primary challenge for future research.

Finally, let us emphasize that we always used the detection probability as payoff function and, in case of variable sampling, the false alarm probability as boundary condition, i.e., we always used only technical parameters. This works as long as we consider only one facility, perhaps one state. If we want to determine the optimal distribution of a given inspection effort across different facilities or even states, we have to describe the incentives for falsification. This in turn requires the introduction of utility functions, see [24], and poses another serious challenge – a challenge which, however, is more of an administrative-political than of a scientific nature.

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Atmospheric Radioactivity Monitoring for the CTBT to Detect Nuclear Test Explosions

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1 The Radionuclide Component of the International Monitoring System for the CTBT

Already in 1958, a Geneva Conference of Experts on the Means of Detection of Nuclear Explosions considered radioactive debris as the only indicator that is available for analysis at large distances and that can be used to determine that an explosion has been a nuclear event. Accordingly, ground-based as well as airplane mounted air filtering devices and analysis of the collected fission products were suggested as a means to detect nuclear explosions at distances of several thousand miles and at times of ten to twenty days after the event.

The Partial Test Ban Treaty (PTBT) of 1963 was the first arms control agreement that has been verified by environmental sampling. The main purpose of this treaty was to end nuclear testing in any environment other than underground. Another provision is that underground nuclear testing is prohibited, if the explosion causes radioactive debris to be present outside the territorial limits of the State Party conducting the test. Verification was carried out by National Technical Means (NTMs) and it did happen that a rapid venting or another incident caused radioactive plumes to be transported through the atmosphere and across the borders. In fact, it happened that the radioactivity was transported over thousands of kilometres, detected and traced back to the source.

The Comprehensive-Test-Ban Treaty (CTBT) was negotiated at the Conference on Disarmament in Geneva between 1993 and 1996. It was opened for signature in September 1996. Though the CTBT has been signed by 185 states and ratified by 170 (as of March 2021), it is not yet in force due to its specific conditions for entry-into-force. However, the Preparatory Commission for the CTBT Organisation has a mandate to establish the International Monitoring System (IMS), the International Data Centre (IDC) and prepare the procedures for On-Site Inspections (OSI). This is carried out by the Provisional Technical Secretariat (PTS) based in Vienna, Austria. The goal is to have the completed verification system in place and ready to operate as soon as the CTBT enters into force.

The CTBT has several provisions for verification of compliance. The International Monitoring System consists of four networks with different sensor technologies: seismic, hydroacoustic, infrasound and radionuclides. In addition, the CTBT allows for confidence building measures, consultation and clarification as well as On-Site Inspections.

The purpose of the International Monitoring System (IMS) sensor network is to detect signals that are indicative for nuclear explosions, as well as to identify and to locate nuclear explosions underground, underwater or in the atmosphere. The IMS network will consist of 337 facilities in order to monitor the whole globe. These are 321 stations and 16 radionuclide laboratories. As of March 2021, 302 of these have already been certified, 9 more are installed and 5 are under construction. The IMS has sub-networks with four different sensor technologies. The seismic network will consist of 50 primary and 120 auxiliary seismological stations; the hydroacoustic network comprises 11 stations to monitor all oceanic waters; 60 infrasound and 80 radionuclide stations are being set up [1].

More precisely, the radionuclide network consists of three components: 80 particulate stations, 40 noble gas systems [2] collocated with particulate stations and 16 radionuclide laboratories [3]. The radionuclide component is essential in providing the proof that an explosion detected by other means is of nuclear nature and not a chemical one [4].

The radionuclide stations will take daily samples, conduct the measurement in the field and send the data to the International Data Centre in Vienna. Upon receipt, the pre-analysis is done automatically and then reviewed by analysts for quality control. The results are sent to the member states and stored in a database. The detectors are designed to achieve a high sensitivity. The agreed requirements are to reach a detection limit of at least 30 µBq/m3 for Ba-140 and 1 mBq/m3 for Xe-133.

The waveform monitoring technologies (seismic, infrasound and hydroacoustic) allow for a highly precise location of explosions in time and space. However, only the association with a relevant detection of radionuclides could provide an indication for an explosion to possibly be a nuclear event. In order to facilitate data fusion, i.e. the combination of events from these different sensor technologies, atmospheric transport modelling is applied to determine the possible source region in order to allow for an event correlation in time and space.

It is up to the member states to interpret the signals and make a judgement about suspected treaty violations. Besides of the routine atmospheric monitoring, the CTBT has also provisions for on-site inspections for the case that a consultation and clarification process cannot remove doubts about a suspicious event. On-site inspection will rely mainly on the analysis of sub-soil gases. Underground nuclear explosions do not only generate fission products but also activation products that are useful as indicators during on-site inspections. Especially argon-37 can be generated by neutron bombardment of the calcium contained in the subsurface soil. It forms by an (n,α) reaction on calcium-40 that has a natural abundance of 96.9%.

Atmospheric and underwater tests release a large amount of radioactivity and will easily be detectable. The most likely future scenario for a clandestine nuclear test is an underground explosion. The challenge is to detect traces released into the atmosphere from underground. Even if these tests are designed for full containment, there is always a risk that the containment fails, and radioactivity is released unintentionally into the atmosphere. Radioactive material produced during underground testing could be released into the atmosphere by leaking through geological faults. In addition, operational activities after the nuclear test inevitably cause the release of radioactivity. More than 500 tests at the Nevada Test Site were followed by operational releases within a few days or weeks after the explosion measured at the point of release [5]. The isotopes that are most likely released are gaseous non-reactive fission products. Due to their chemical inertness noble gases are not removed from the atmosphere by wet or dry deposition processes. The only relevant sink of these radioactive nuclides in the atmosphere is their radioactive decay. Therefore, traces of radioactive noble gases could be detected at large distances from the source. This behaviour makes the radioactive noble gas isotopes attractive as indicator for the detection and verification of nuclear activities. Due to their fission yield and half-life, there are four CTBT relevant noble gas isotopes, Xe-135, Xe-133m, Xe-133 and Xe-131m [6].

The radioactive xenon isotopes that are produced by the fission of uranium and plutonium have very large fission yields of up to approximately 7%. The challenge of using these isotopes as indicator for nuclear explosions results from the fact that many nuclear facilities release the relevant isotopes as normal operational release [7]. Source characterization is possible by investigating the isotopic activity ratios. The establishment of what constitutes a typical atmospheric background concentration is also useful to distinguish between normal and anomalous observations. This results in frequent detections of elevated concentrations.

In order to avoid false alarms, it is important to be able to discriminate between reactor emissions and releases from nuclear explosions. It has been shown that isotopic ratios can be utilized for source discrimination [8]. If only a single isotope is measured with the others being below the detection limit, it is still possible to associate the detection to a possible source region by atmospheric transport simulations [9].

Since the first nuclear weapons were built several laboratories world-wide developed manual and automated techniques to collect and measure radioactive noble gases in the air, in soil gas and in the ocean with high sensitivity. The measurement of the atmospheric concentrations of noble gases requires a five step procedure: (1) noble gas collection and concentration (2) further enrichment and purification, (3) activity measurement, (4) determination of the volume of stable noble gas volume in the counting device and (5) calculation of the atmospheric activity concentration in Bq per m^3 of air.

The collection of the relevant gas and the avoidance of other components in the sample require the complete elimination of nitrogen, oxygen, carbon dioxide, water, radon and other trace elements. Dryers and chemical sieve traps are used for purification. Another basic principle for the separation of noble gases from the air is the adsorption and desorption of the noble gases at activated charcoal at different temperatures (-193°C to 300°C). After further fine purification steps using standard gas purification techniques the relevant noble gas fraction is transferred into counters. The activities are measured and the gas volume of the noble gas component is determined. Based on the worldwide constant stable argon (0.93 %), stable krypton (1.14 ppm) and stable xenon (0.087 ppm) in the atmosphere an equivalent air volume could be calculated. In the northern hemisphere the atmospheric background level of Xe-133 is around a few mBq/m^3. In many areas of the southern hemisphere the mean atmospheric activity concentration of Xe-133 is well below the detection limit of the existing systems of < 1 mBq/m^3. Special counting techniques have to be applied to detect these low activities.

During the last decade, special efforts were undertaken for the simultaneous detection in atmospheric samples for the four CTBT relevant isotopes and isomers of xenon (Xe-131m, Xe-133, Xe-133m and Xe-135) [10]. Two different techniques were further developed for their use in fully automated systems for xenon monitoring: (1) High-Purity Germanium (HPGe) Gamma Spectrometry and (2) the Beta-Gamma Coincidence technique. A HPGe gamma detector was integrated into a xenon monitoring system with special emphasis on low detection limits in the order of mBq/m^3 or below for the CTBT relevant isotopes of xenon. Further improvements in sensibility are also reached by evaluating the X-rays emitted in the decay of the radio-xenons in the energy range between 28 and 37 keV. The other approach to reach the required high sensitivities is the simultaneous measurement of the electrons and photons by the beta-gamma coincidence technique. The xenon sample is contained in a scintillation cell that serves also as electron detector. The scintillation cell is surrounded e.g. by a Na(I) for the detection of the photons in coincidence to the electrons. The advantage of this method is the very low background together with a very high detection efficiency, which allows the detection of very low activities. In comparison to the HPGe detection system, the coincidence method needs a smaller sample volume to get the same sensitivity, if all other conditions, like counting times, are the same. The development is going towards the beta-gamma coincident technique and all systems of the new generation apply this approach.

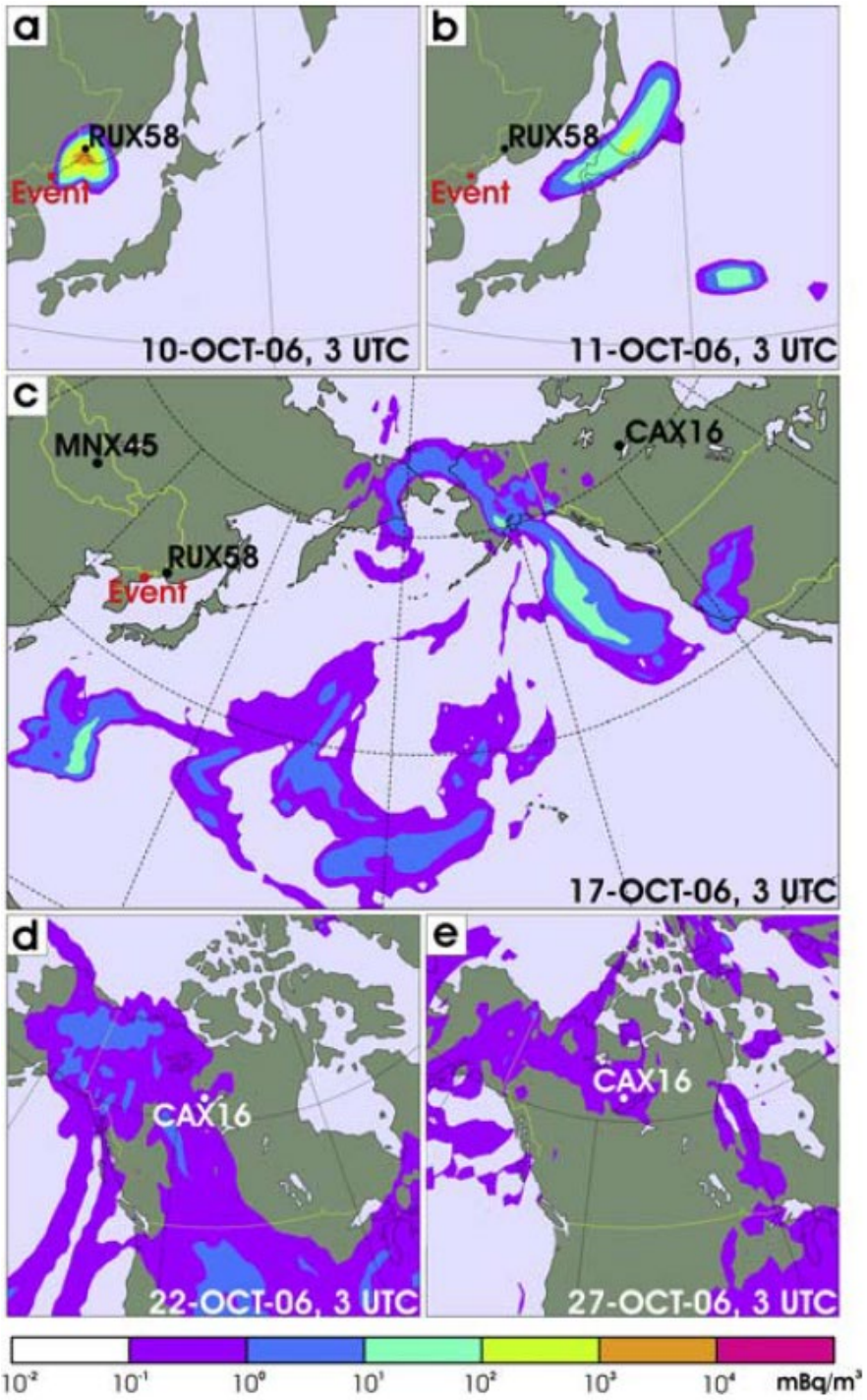

Figure 1: "Calculated ground level concentrations of 133Xe based on a 1 PBq emission at the time and coordinates of the 9 October DPRK explosion. The most interesting stages of the plume evolution are illustrated. (a) The initial dispersion from the event location (red dot) towards northeast reaching the scheduled PTS radio-xenon station RUX58 (Ussuriysk, Russian Federation). (b) The plume after two days when it passes Hokkaido, Japan. (c) After eight days, when its eastward evolution is decelerated by the mountain ranges of western North America. (d, e) The times when the plume is analysed to create the first and second peak at the PTS station CAX16 (Yellowknife, Canada). The station RUX58 was not installed at the time of the event." [11].

2 Successful Detection of Radionuclide Signals from Nuclear Tests Announced by the DPRK

The announced nuclear test undertaken by DPRK on 9 October 2006 was a chance to demonstrate the functionality of the radioxenon monitoring system [11].

On 26 February 2008, Tibor Tóth, the Executive Secretary of the Provisional Technical Secretariat said: *"We also need to continue building up the noble gas technology. Data from this technology were crucial in the context of the declared nuclear explosion in the DPRK in October 2006."* [12]

Several seismic observatories all over the world recorded an event that took place in the North East of the country at 1:35 UTC on that Monday with a seismic body wave magnitude of 4.1±0.1. The Provisional Technical Secretariat (PTS) of the CTBTO PrepCom determined the location and time of the event from seismic signals received at the IMS stations. This was reported in the daily Reviewed Event Bulletin (REB) to the member states. Seismic analysis can in principle conclude if a seismic event was caused by an explosion or by an earthquake. In this case the signals were weak, but nevertheless indications are strong that the event was an explosion. However, the low yield estimated to be in the range of 0.5-0.8 kt TNT raised the question whether the explosion was caused by chemical explosives or by a nuclear one.

Seismic signals cannot be used to make this distinction. In order to proof undoubtedly the nuclear character of an explosion it is necessary to detect radioisotopes produced in the nuclear fission processes and relate them with atmospheric transport modelling (ATM) to the geographic region of the explosion as demonstrated in Figure 1. This was successfully achieved even though the IMS network of noble gas stations was far from being complete. At that time there were only ten stations under experimental operation and not a single at close distance. The success is described by the PTS with the following words: [13]

> *"According to ATM calculations, the debris would reach the nearest operating noble gas station in Yellowknife, Northern Canada, on 22 October 2006 with two peaks on the 23rd and 27th. Interestingly, alternative forward ATM calculations with up to two days delay in release times predicted the same double peak signal. This indicates that the peak pattern at Yellowknife was rather shaped by the geographical conditions (i.e. mountain ranges in Alaska and Northern Canada) than by the release time of the device. The station in Yellowknife detected, as predicted, above background levels of xenon-133 on 21 and 25 October with somewhat lower values between 22 and 24 October, thus resembling the calculated double peak pattern. Backtracking calculations were evaluated to exclude other known sources of noble gas from facilities closer to the station. Consequently, the ejection of xenon-133 characteristic for a one-kiloton nuclear explosion on the Korean peninsula at the time of the REB event was the most realistic source scenario to explain the observed concentration pattern in Yellowknife."*

Though the IMS system together with atmospheric transport modelling (see Figure 1) delivered a strong indication for the DPRK explosion being of nuclear nature.

Also the USA applied environmental sampling as national technical means to confirm that the seismic event recorded in the DPRK was in fact a nuclear test. The short statement released by the USA is quoted in full length here: [14]

> *"Analysis of air samples collected on October 11, 2006 detected radioactive debris which confirms that DPRK conducted an underground nuclear explosion in the vicinity of P'unggye on October 9, 2006. The explosion yield was less than a kiloton."*

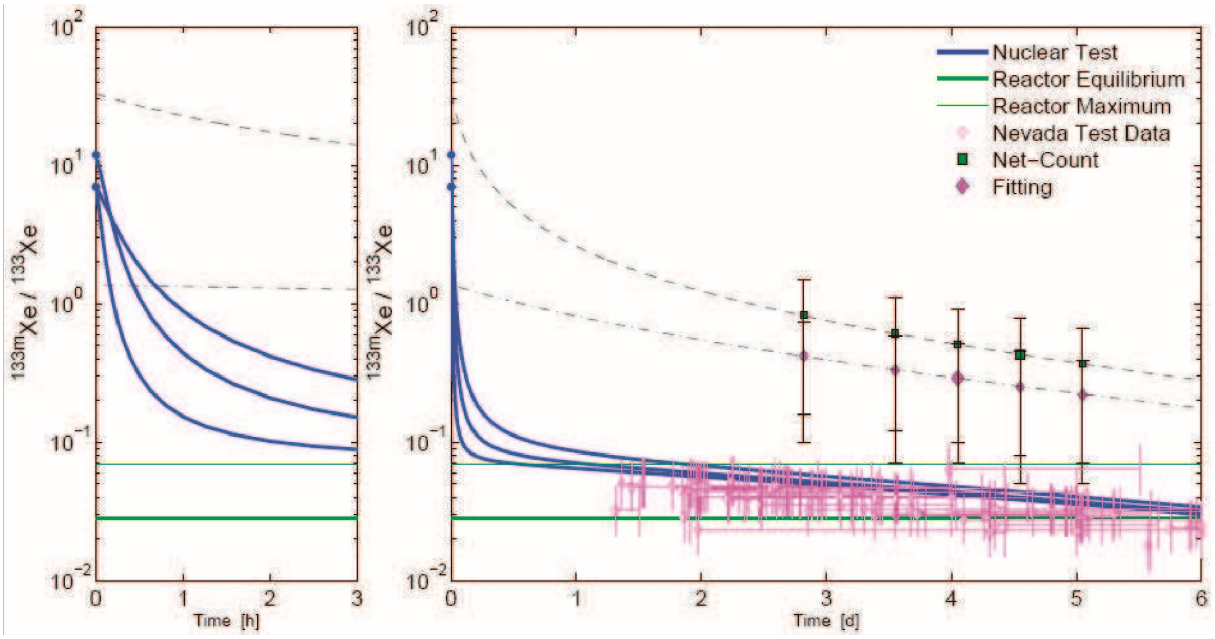

Figure 2: Isotopic ratio of Xe-133m/Xe-133 as it develops over time after the explosion. The data from samples taken in South Korea in October 2006 are put in perspective with historic data from the Nevada Nuclear Test site and simulated curves that follow the radioactive decay for various scenarios.

Fortunately, a Swedish team had quickly after the explosion offered to South Korea to take air samples with their mobile noble gas extraction unit and analyse them for radioxenon with a device called SAUNA in their laboratory in Stockholm. They succeeded in detecting all relevant isotopes but Xe-135 in five samples taken on the west coast close to the Demarcation line between the two Korean states between 11 and 14 October [15]. Air trajectories indicated that a plume released from the explosion site would have reached the air sampling point at the time when radioxenon was detected a few days after the explosion.

The detection of multiple isotopes allows for applying nuclear forensics methods using isotopic activity ratios. At first glance, the isotopic ratios including Xe-131m appeared like those emitted from nuclear power reactors while the ratio of the isomers Xe-133m and Xe-133 indicated an explosion as described below. It took a couple of more months before the ambiguity was erased and a clear picture emerged. The Swedish team continued air sampling for four more months to analyse the typical background on the Korean peninsula. These measurements revealed that the Xe-131m concentration measured in October 2006 is at the typical background level in that area. Accordingly, it was not part of the plume freshly released by the nuclear explosion but it remained from releases of nuclear reactors during the previous weeks. This occurs with this particular isotope because it has the longest half-life of the relevant four isotopes (11.9 days). This insight demonstrates clearly the high value of continuous monitoring in contrast to spot samples. Only with a time series of data over some time can reveal the atmospheric background and allow drawing conclusions about the relevance of detections.

With this insight, only the two isomers Xe-133m and Xe-133 remained for an analysis of their activity ratio. Figure 2 shows the measured and reconstructed data for the five samples with elevated concentrations in October 2006. Two different analysis approaches were used and reported by the Swedish team. The operationally used net count method and a more precise fitting method. The latter provides lower concentration values. Each method was able to determine the activity concentration of both isomers for one of the five samples (indicated by thicker marks in Figure 2). This paper uses a reconstruction of the missing values according to the radioactive decay law.

Figure 2 demonstrates how the activity ratio of Xe-133m/Xe-133 develops over time after the explosion. It puts the measured data points in perspective with simulated ratio curves [16] as well as historic data as reported from the Nevada Test Site [17].

The solid blue simulation lines apply for nuclear explosions under the assumption that the gaseous radioxenon remains in contact with the precursor nuclides (no fractionation). The dashed black curves follow simply the radioactive decay of both isomers assuming full fractionation. The green lines mark the equilibrium and the maximum ratio that occur in nuclear reactors. The Nevada data lie in the range of the reactor ratios and suggest that no discrimination is possible later than a few hours after the explosion when the blue curves resulting from nuclear explosions bent down towards the reactor domain.

However, the Korean data are found clearly above this range. This can be explained by an early fractionation of the gaseous from the non-volatile fission products. Within one hour, the radioxenon must have been emitted from the underground explosion leaving the particle bound precursor nuclides behind. Until that time, the ratios have followed one of the blue non-fractionated explosion scenarios. From the time of emission, the activity ratios followed the dashed line of decay without ingrowth of the precursors. This resulted in activity ratios well above the reactor domain and render source discrimination possible even five days after the explosion. A clear proof is found that the DPRK explosion of 9 October 2006 was of nuclear character. The Swedish team itself was the first to reveal this result. This demonstrates that isotopic ratios can successfully be utilized for source discrimination, even if only the two different isomers Xe-133 and Xe-133m were quantified per sample.

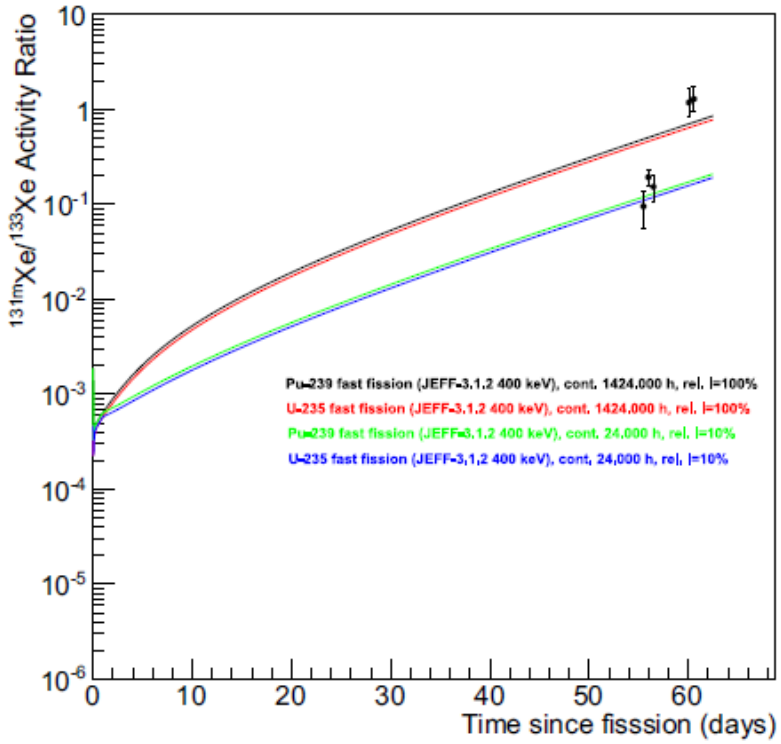

Figure 3: The plot shows the isotopic ratio of Xe-131m/Xe-133 as it develops over time after the explosion based on four different scenarios with regard to the fission material and fractionation. The two upper curves assume full ingrowth of all precursors until release and fit best the samples taken at RN58. The two lower curves assume separation of xenon and 10% of iodine after 24 hours [18].

The third nuclear test announced by DPRK on 12 February 2013 did not cause a radionuclide signal at an IMS station from a vent promptly following the explosion. However, in April 2013, several conspicuous radioxenon observations were made by the IMS stations RN38 in Takasaki, Japan, and RN58 in Ussuriysk, Russian Federation. Three consecutive samples collected on 7 and 8 April at the IMS radionuclide station RN38 in Takasaki, Japan, and two samples collected on 12 and 13 April at RN58 had anomalous concentrations. These samples were found by [18] and [19] to be indicating a delayed release from the underground nuclear test announced by the DPRK on 12 February 2013. By atmospheric transport simulations it was shown that the observations are consistent with the assumption that the source was a delayed release from the DPRK test site. A variety of possible release scenarios was taken into consideration. As can be seen in Figure 3, the analysis of isotopic ratio changes over time for a plausible scenario showed that about 55 days before the observation the isotopes had the composition of a fresh fission reaction. This zero-time estimate matched exactly the date of the announced DPRK test. As a result, the isotopic ratios recorded in April 2013 are considered a strong evidence for the nuclear nature of the seismic event of 12 February 2013.

3 Atmospheric Transport Modelling

3.1 Introduction

Remote detection of relevant radioactive indicators in the environment poses a strong opportunity for treaty verification. Whatever the purpose is, the full potential of this method depends on the capability of source attribution. The scientific advances made in the science of atmospheric transport modelling offer powerful methods for determining a certain geographical area as possible source region and for estimating the source strength. Especially if two or more detections are related to the same source, correlations in the source-receptor relationships facilitate a useful localisation precision. This can be further enhanced, if additional information is available like the time of the release.

Many attempts have been made in recent years to develop and improve global numerical models to simulate atmospheric transport and chemical reactions of gaseous and particulate constituents as well as the manifold interactions between meteorology and chemistry [20]. Atmospheric dynamics and cloud processes control the concentration and distribution of atmospheric constituents. Winds transport gaseous and particulate matter and loft dust and sea-salt aerosols into the atmosphere. The intensity of the solar radiation and the temperature determine the chemical reaction rates. Cloud droplets are chemical reactors and contribute to the formation of aerosol particles and the precipitation cleans the atmosphere from gases and particles.

The Provisional Technical Secretariat of the CTBTO Preparatory Commission in cooperation with the World Meteorological Organisation has put a ground-breaking approach for source location in an operational mode. Atmospheric modelling is applied for this and other purposes [21], [22].

3.2 Methods for Global Atmospheric Transport Modelling

Global atmospheric transport and dispersion of tracers can be calculated either with Eulerian or with Lagrangian models. GCMs (Global general circulation models) and CTMs (Chemistry Transport Models) use the Eulerian method to calculate the large-scale transport of atmospheric constituents by wind (three-dimensional advection) and subgrid-scale vertical transport by turbulent exchange and within clouds. Horizontal diffusion of trace constituents is mostly neglected. Generally, these transport processes are calculated in the same way as the transport of water vapour. The advection equation for the trace constituents is $\partial q/\partial t + v \nabla q = 0$, where q represents a “mixing ratio-like” quantity and v is the wind vector. This equation is solved with a numerical method.

HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory Model) and Flexpart (FLEXible PARTicle dispersion model) are global dispersion models based on the Lagrangian method. This method simulates air parcels travelling with the general circulation of the atmosphere as interpolated from meteorological input data. These input data are generated by a Global Spectral Model e.g. at the US National Centre for Environmental Prediction (NCEP) or at the European Centre for Medium-Range Weather Forecasts (ECMWF). HYSPLIT and Flexpart can compute plumes both in the backwards as well as in the forward analysis mode for each site where a radionuclide station is located.

3.3 Determining Optimal Station Placement and Procedures

During the negotiations of the CTBT at the Conference on Disarmament in Geneva, various possible designs for the global network of radionuclide stations were discussed. The network was optimised by atmospheric transport modelling studies undertaken by several countries with the goal to detect a 1 kt nuclear explosion within 14 days and with a certain detection probability (90% for atmospheric explosions). Basic design criteria for the network were derived from four different scenarios and related performance criteria for detection, identification, and location. These scenarios were nonevasive as well as evasive atmospheric, underwater and underground explosions. Existing national stations that many countries had established and operated over several decades were considered as candidate sites.

As a result, 80 radionuclide station locations were selected and listed in the Protocol to the CTBT. At that time, it was left open where the 40 noble gas stations should be located and whether the noble gas network should be expanded to all 80 sites. As a result of further network design studies undertaken by the France, Canada, and USA 40 out of the 80 sites were chosen by the Preparatory Commission in 1998 as a start to locate noble gas detection systems.

The optimum procedures for wide-area air sampling under the NPT Additional Protocol are not yet sufficiently determined. This has to be based on a reasonable detection goal that is related to the significant quantities of plutonium and highly enriched uranium as well as to the timeliness goals as defined by the IAEA. In particular, the detection and false alarm probabilities as well as the detection sensitivity (minimum amount/rate of plutonium separation and uranium processing) need to be determined. This will be dependent on the geographic dimensions considered for wide-area air sampling. These performance parameters will have to be determined under certain assumptions. These are different material production scenarios, sampling procedures like sampling period and number of sampling sites and the distance from a source. The current state of thinking is that the monitoring of key radionuclides like krypton-85, iodine-129 and iodine-131 might work at distances up to 100 km. It is likely that this range can be significantly improved by determining the background concentration from global atmospheric transport modelling and nested regional models by making use of the known sources of these isotopes.

3.4 Source Localisation

The first attempts of atmospheric transport modelling to locate the origin of detected radionuclides used wind fields to determine the trajectories of single particles. These could be considered as indicating the centre of a plume. If time is reversed in the model, the locations passed by back-trajectories would be considered as potential origins of a radioactive release. More advanced methods modelled dispersion in a plume with time-inversion by inverse modelling resulting in so-called retro-plumes.

However, single sample modelling without event time information does not allow for a meaningful source location. With every time-step, the potential source region increases. Allowing for transport times of about 10 to 14 days, almost any location on a whole hemisphere could be the origin of a particular detection. If

multiple samples at the same site or at different locations are related to the same release, the correlation of source-receptor relations can result in significant confinements of the possible source region. The more samples are combined in the network analysis, the more precise can the source location be determined.

In order to support the CTBT member states, the International Data Centre (IDC) runs its own atmospheric transport models for routine operations and cooperates with the World Meteorological Organisation (WMO) to do more extensive modelling for relevant cases. A framework agreement between the Preparatory Commission for the CTBTO and the WMO was finalised in 2001 and soon after put in operation. Under this agreement the WMO Regional Specialised Meteorological Centres run their models to determine potential source regions for radionuclide events of interest. The IDC runs the atmospheric transport model Flexpart as operational model that calculates with backward plumes for every sample the source-receptor sensitivities for all grid-points on the globe. The simulations are driven by meteorological analysis data from the ECMWF.

Various possible products can be generated with atmospheric transport modelling. In order to account for the inherent uncertainties of modelling atmospheric processes, the standard presentation of results considered for CTBT purposes is the so-called field of regard (FOR). This means that the shown geographical area is only indicative for a possible source region and, therefore, is a field that can be taken into regard for further investigation. The FOR is defined as the geographic area indicating possible sources of air that may have contributed to the radionuclide measurement at a specific station within a specific sample collection period. In estimating this area certain assumptions have to be made (e.g. source at ground level). The FOR is a function of certain parameters, especially the transport time and dilution ratios. Especially, the geographic area depends on time and is the larger the longer the radio-active plume travel time is assumed to last.

The origin time of a radionuclide event can be determined only, if suitable isotopic ratios can be calculated. Plume age information would confine the FOR area to be meaningful for source location. If the origin time is not known, standard FORs are shown e.g. for 24-hour, 48-hour, and 72-hour periods prior to the collection stop time.

An enhanced version of the standard FOR quantifies for each region and point in time the maximum release concentration that is consistent with the collected sample. This value can be derived either from the measured concentration at the detector site or – if this is not available – from the Minimum Detectable Concentration by accounting for the dilution caused by turbulent mixing, scavenging, and other processes along the transport path.

A significant reduction of the possible source area as well as a determination of the origin time can be achieved by inverse multi-sample modelling, i.e. by combining FORs that are related to different detector sites (network analysis) and to more than one collection period (consecutive sample analysis). Under most favourable meteorological conditions, the best achievable accuracy is in the order of the model resolution. The state-of-the-art is a resolution of 1 hour and 0.5° times 0.5° for longitude and latitude. Rejecting and confirming areas that are covered by FORs related to other samples can confine the possible source region of a particular event. The confirmed region can be defined by the union of all geographic areas which are matching in travel time estimate for all sites that detect the same event (positive indication). The region can be further confined by cutting off those areas that have matching travel times and are related to samples in which the relevant radionuclide is not detected (negative indication).

The method of choice for calculating FORs and combining them is to calculate the source-receptor sensitivity matrix which contains the transfer functions between all possible regions for a radioactive release, the sources, and all detector sites, the receptors [22]. The source-receptor matrix can be calculated by transport and dispersion models operating in backward mode to calculate the retro-plume from the detector sites. Depending on the conditions, the inverse modelling with multiple samples may be solvable only with so-called

regularisation, i.e. the input of a-priori knowledge, which may especially be either the origin time or the location [22]. This could be applied for hypothesis testing related to seismoacoustic events that might be source of the radioactivity.

A further significant reduction in possible source area can be achieved, if the origin time of the detected radionuclides can be estimated. Given the presence of certain isotope pairs with suitable half-lives in the sample, isotopic ratios could be utilised to determine the age of the sampled plume. Useful isotope pairs based on particulate samples are Ba-140/La-140, Nb-95/Zr-95 [23], and based on noble gas sampling Xe-133/Xe-131m, Xe-133m/Xe-133, and Xe-135/Xe-133 [24]. The advantage of the latter is that they are not distorted by fractionation effects. A plume age probability distribution can be derived from the error associated with the isotopic concentration ratios. Since the elements of the source-receptor-matrix are a function of the travel times they can be multiplied by the plume age distribution to get the source probability matrix as a function of space and time.

The source probability could be even further improved, if information about the release scenario, especially the source strength probability distribution, is available.

4 Conclusions

The CTBT monitoring for nuclear explosions is based on four different sensor technologies. Atmospheric radioactivity sensors play an important role since nuclear debris could provide a clear evidence of a nuclear explosion while the waveform technologies can precisely locate explosions but not determine whether they are of chemical or nuclear nature. However, it needs to be taken into consideration that radioactive emissions frequently occur from legitimate sources, in particular for radioactive noble gases. The risk of false alarms has to be minimized by smart analysis methods, e.g. nuclear forensics using isotopic activity ratios. Their fundamental principles have been developed and their applicability has been successfully demonstrated for the nuclear tests announced by the DPRK in October 2006 and February 2013.

Disclaimer: The views expressed in this article are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.

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Use of Commercial Satellite Imagery in Support of Non-Proliferation

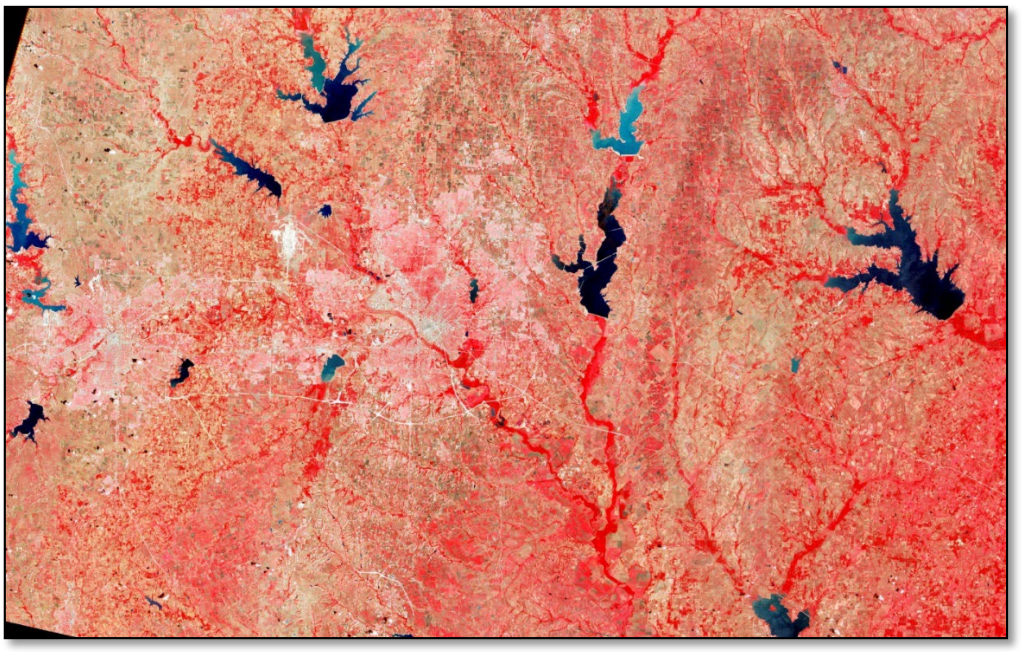
Marc Lafitte and Aurélien Collet

SatCen - European Union Satellite Centre (Spain)

Satellite Imagery, the Genesis

The first civilian remote sensor on a space-borne platform and commonly known as Landsat-1 (originally named ERTS-A Earth Resources Technology Satellite) was launched from the Vandenberg Air Force Base on 23 Jul 1972. From an orbit of 900 km the multispectral scanner (MSS) supplied satellite imagery with a ground sample distance (GSD) of 80 metres.

Military programs such as CORONA, the first US military satellite-based reconnaissance program, had already been operating since August 1960.



The first fully operational Landsat image taken on July 25, 1972 - ©NASA's Earth Observatory

On 17 July 1984, almost five years after the launch of the fifth satellite of the Landsat series[103], US Congress passed the Land Remote Sensing Commercialization Act, which provided for the privatisation of land satellites and therefore the commercialisation of data.

Placed in orbit at 700 km, Landsat 4 and 5 carried **Thematic Mapper** (TM), an earth-observing sensor that features seven bands of image data (three in visible wavelengths, four in infrared) most of which have a 30 metres spatial resolution. The orbit allowed an acquisition frequency over the same point on earth - repeat interval - of 16 days.

[103] Landsat 5 launched on 1st March 1984

The first European earth observation satellite, SPOT 1[104], was launched from the Kourou Space Centre on 22 February 1986 and carried **HRV** (high resolution visible) imaging instruments. It was capable of delivering a panchromatic band (10 m GSD) and three multispectral bands (20 m GSD) from an orbit of 800 km.

SPOT 1 First Image over Chernobyl
©CNES 1986, Distribution Airbus DS

Imagery from SPOT 1 acquired over Chernobyl Nuclear Power Plant on 06 May 1986, 10 days after the nuclear accident, was widely displayed. It foreshadowed the upcoming use of commercial remote sensing data to strengthen non-proliferation efforts and the monitoring of nuclear facilities.

In 1997, the International Atomic Energy Agency (IAEA) Board of Governors (BOG) adopted the Additional Safeguards Protocol. The purpose of the protocol is to enhance the IAEA's ability to detect the undeclared production of fissile materials in member states.

From Correctness to Completeness

Trust But Verify!

Since the beginning of the 1990s, remote sensing has become the most effective and efficient solution for treaty verification, as well as monitoring the safety and security of nuclear facilities.

'Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance from the targeted area'

Source : U.S. Geological Survey (USGS)

'Remote sensing is defined as the science and technology by which characteristics of objects of interest can be identified without direct contact'

Source : International Society for Photogrammetry and Remote Sensing (ISPRS)

Over the last four decades, the capabilities of satellite imagery and associated remote sensing and geospatial techniques have increased. The unprecedented very high-resolution (VHR) data that is currently available, the

[104] SPOT : Satellite Pour l'Observation de la Terre

improved spectral capabilities, the increasing number of sensors and ever-increasing computing capacity, have opened up a wide range of new perspectives for remote sensing applications.

The following chapters review the benefits provided by the suite of sensors and associated remote sensing techniques based on electromagnetic measurements acquired from space-borne platforms with regard to the monitoring of nuclear facilities.

Analysis of satellite imagery is routinely used in the following activities:

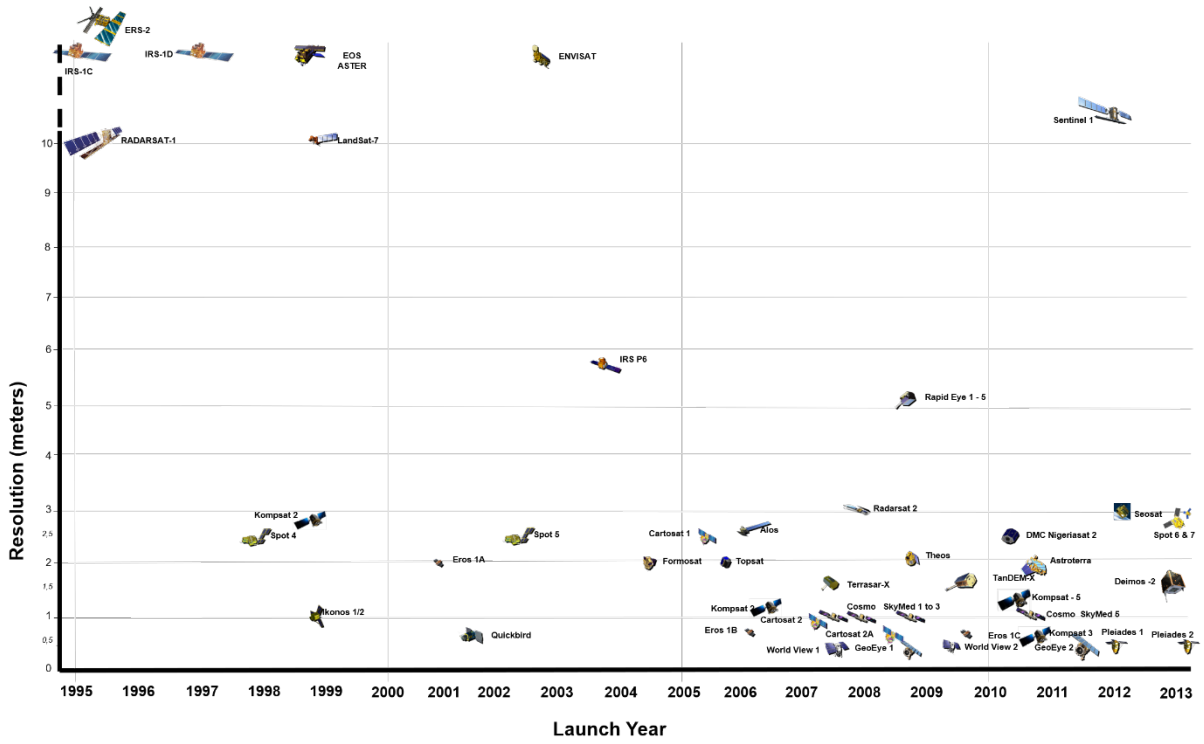
- to verify the accuracy and completeness of information supplied by states;
- to aid the planning of in-field and inspection activities;
- to detect changes and monitor activities at nuclear fuel cycle-related sites; and,
- to identify possible undeclared activities.

Commercial satellite imagery has become a very important information source for the IAEA's Department of Safeguards, especially regarding places where the IAEA does not have access.

IAEA
International Atomic Energy Agency

The Sensors

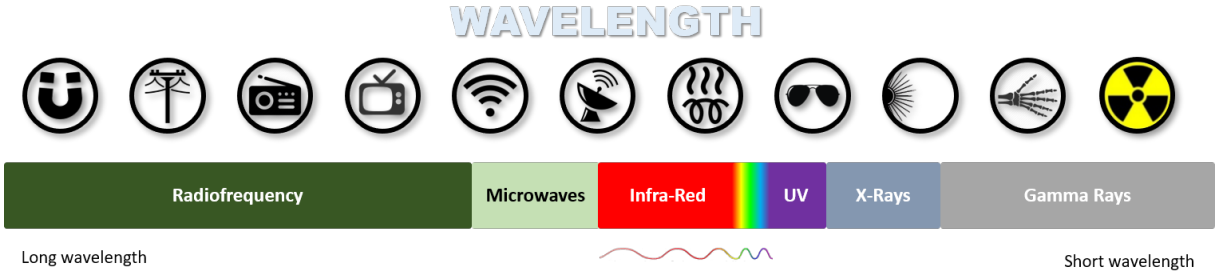
Since the 1990s, the number of commercial space-based remote sensing platforms has steadily increased with an acceleration of the trends being seen over the last decade.



In 2018, more than 300 meteorological and earth observation satellites were sent into orbit (source: Observing Systems Capability Analysis and Review Tool).

Nowadays, hundreds of earth-observation satellites are commercially available worldwide. Of the wide range of sensors available, the selection of the most suitable and efficient sensor is key to broadening out remote sensing techniques and to strengthening analysis.

The electromagnetic (EM) spectrum is the range of all types of EM radiation (wavelength). Space-based remote sensors are routinely designed for the measurement of a specific part of the electromagnetic spectrum, which is reflected and emitted from earth.



Electro-Optical (EO) Sensors

The performance of EO space-based sensors is commonly described and characterised by the following parameters, also known as the '3R':

- **The Spatial Resolution**
- **The Spectral Resolution**
- **The Temporal Resolution**

Synthetic Aperture Radar (SAR) Sensors

Unlike an EO sensor, a SAR antenna is an active and coherent sensor working in the microwave domain of the electromagnetic (EM) spectrum. It collects the backscatter signal of an electromagnetic wave. This electromagnetic wave is characterised by two fundamental properties: amplitude and phase.

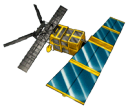
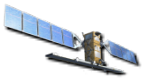
- **The amplitude** is a function of backscattered energy displayed as intensity ($I = A^2$) and can be considered as the 'visual' part of the information. The behaviour of the backscattered electromagnetic energy depends on the interaction between the electromagnetic wave and the physical and dielectric properties of the target; the roughness and the moisture. Some materials such as metal have a high reflective quality while others such as grass have a poor capacity to reflect incidental energy.

- **The phase** is a property of a periodic phenomenon which is the fraction of one complete sine wave cycle (from $-\pi$ to $+\pi$) corresponding to the wavelength. It is a key element for the estimation of displacement (sensor-to-target distance) and thus used for interferometric measurement. The analysis of differences between phases of reflected radiation is called interferometry. There are two main possible sources of phase shift: vertical (terrain altitude) and horizontal (terrain motion).

The processing of the backscatter signal collected by the multiple antenna locations, which form the synthetic antenna aperture, allows the formation of a matrix of pixels in two dimensions: range and azimuth (cross

range). Space-borne SAR sensors use L, C or X-band and most of them are able to emit and receive with various polarisations (i.e. multi-polarisation). These bands provide different spatial resolution and a range of capabilities regarding ground and foliage penetration.

On 17 July 1991, the first earth-observing SAR platform, the European Remote Sensing satellite (ERS) was sent into orbit. Since then, European countries and various consortiums have demonstrated enthusiasm for space-based SAR sensors.

ERS-1/2	Sentinel-1	Terrasar-X	TanDEM-X	PAZ	Cosmo SkyMed 1-3
					

Remote Sensing Techniques

The capabilities of space-based electromagnetic sensors have evolved tremendously over the last four decades. Meanwhile, the huge advances in computing power and associated communications technologies have strongly supported the development of a wide range of applications utilising satellite imagery. Currently, almost any part of the earth can be easily imaged in high resolution (HR) or even very high resolution (VHR) through web applications.

The nuclear fuel cycle is the set of industrial processes that make use of nuclear materials for the production of electricity. Most of these processes can be scrutinised and assessed using remote sensing techniques based on the analysis of satellite imagery.

The analysis of satellite imagery and associated remote sensing techniques are grounded in the sensor's three main abilities, which are the **spatial**, **spectral** and **temporal** resolutions.

Spatial Resolution

Spatial resolution is the capability to distinguish, 'resolve' or separate small details from their context. It is a measure of the finest detail distinguishable in an image.

'Spatial resolution is a measure of the smallest object that can be resolved by the sensor'

jmu.edu

'The spatial resolution of a raster represents the area on the ground that each pixel covers'

Earthscience.org

'The detail discernible in an image is dependent on the spatial resolution of the sensor and refers to the size of the smallest possible feature that can be detected'

nrcan.gr.ca

The most commonly used descriptive terms for spatial resolution is the ground sample distance (GSD).

GSD is commonly categorised along the following scale of spatial resolution:

- Low resolution: larger than 30 m
- Medium resolution: 2 to 30 m
- High resolution: under 2 m
- Very high resolution: sub-metre

The tremendous gain in spatial resolution achieved over the last three decades and the unprecedented amount of very high resolution (VHR) data that is currently available has opened up a wide range of new perspectives for imagery analysis and remote sensing applications.

Chernobyl Nuclear Power Plant

20 m GSD

SPOT 1
© CNES 1986, Distribution Airbus DS

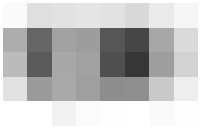
60 cm GSD

Pléiades-1, 05 Jun 2017
©2017, Airbus DS

Satellite imagery and associated remote sensing techniques are applied and analysed by humans. A range of motivational and emotional factors that undoubtedly influence the processing of visual stimuli drives this analysis.

Our eyes do not send images to our brains. Images are constructed in our brain based on the very simple signals sent from our eyes. We only 'see' after the brain has interpreted what has been sent by the eyes. The human brain forms images based on pattern recognition learned at an early age.

Human analysis of satellite imagery relies on the detection, recognition or identification (DRI) of features or elements. The highest spatial resolution significantly benefits human analysis.



Detect a vehicle

Recognise a light car

Identify a BMW series 1

The quality of satellite imagery can be expressed in technical terms like the ground sampling distance (GSD). Nevertheless, in order to provide a more objective standard of image quality, the US Government's Imagery Resolution Assessments and Reporting Standards (IRARS) Committee established in the early 1970s a rating system: the National Image Interpretability Rating Scales (NIIRS). This system defines and measure the quality of images and the performance of imaging systems by quantifying/predicting image interpretability.

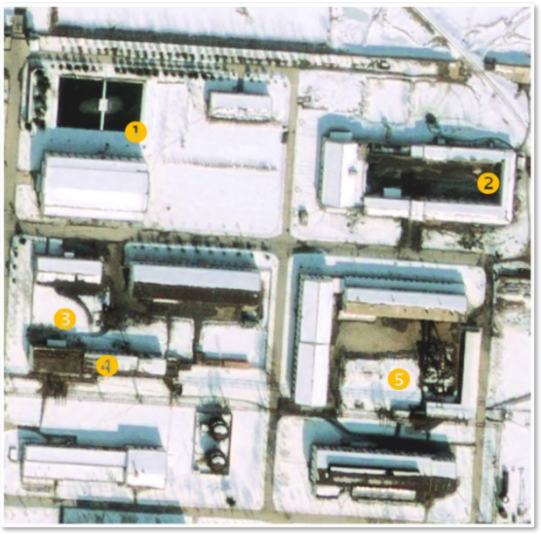
NIIRS 1 (4.5-9m)	NIRRS 5 (0.75 - 1.2 m)	NIIRS 9 (> 0.10 m)
Able to distinguish between major land use classes (e.g. urban, agricultural, forest, water, barren). Detect a medium-sized port facility. Distinguish between runways and taxiways at a large airfield. Identify large area drainage patterns by type (e.g., dendritic, trellis, radial).	Able to identify individual rail cars and locomotives by type. Detect open bay doors of vehicle storage buildings. Identify tents (larger than two persons) at established recreational camping areas.	Able to identify individual grain heads on small grain (e.g. wheat, oats, barley). Detect individual spikes in railroad ties. Identify an ear tag on large game animals (e.g. deer, elk, moose).

Tips for Visual Analysis

The low solar incidence during winter periods provides extended shadows that can significantly enhance the analysis of vertical features.

1. Stack
2. Metallic frame structure
3. Trees
4. Vertical silos
5. Tall building

Snow covered imagery may also reveal useful indicators of human activity, such as vehicle tracks, heat, etc.



1 Water pond active
2 Snow cleared
3 Truck track
4 Smelted snow
5 Snow cleared

Spectral Resolution

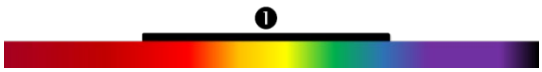
Spectral resolution is commonly applied to EO sensors, optical and infrared, that measure reflected or radiated energy. A sensor's spectral resolution is based on the number of bands, their location along the electromagnetic spectrum and how narrow the bands are.

Panchromatic sensors acquire data from a single broad region of visible light and sometimes also from the adjacent near-infrared end of the electromagnetic spectrum. Multispectral sensors are capable of simultaneously acquiring from 3 to 10 wider bands while hyperspectral instruments can capture hundreds of narrow bands.

Most of the space-borne sensors have panchromatic and multi-spectral measuring capabilities.

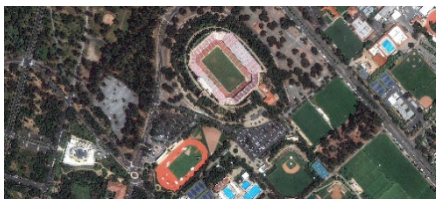
A panchromatic image

Eros-B imagery - © 2016 ISI

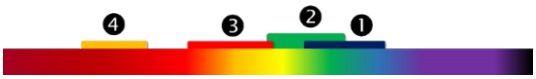


1 band acquired

A multispectral image



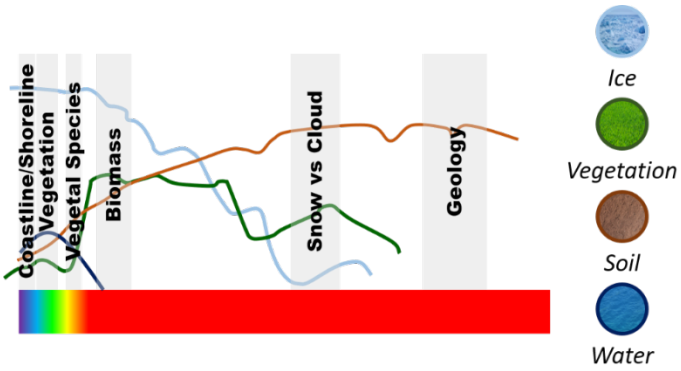
Pléiades-1 imagery - © 2017 Airbus DS



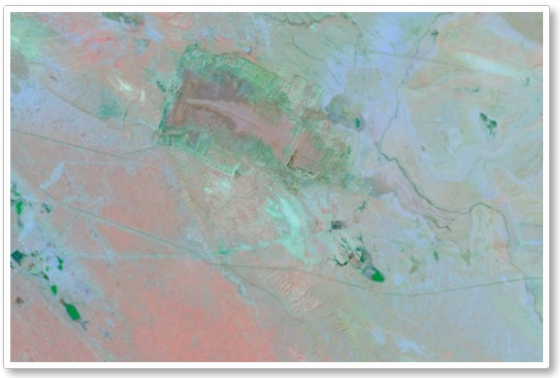
4 bands acquired

Analysis of Multi-Spectral (MS) Imagery

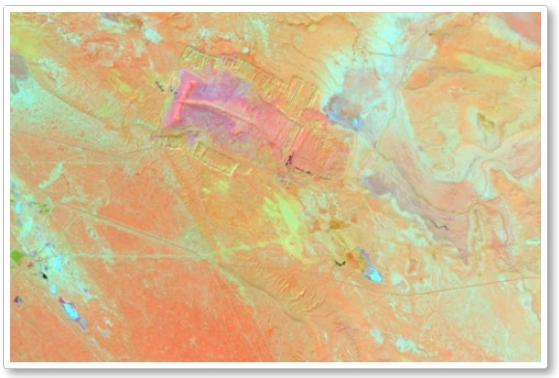
The ability to simultaneously collect radiation from multiple narrow wavelengths, in particular the reflected infrared (including near infrared "NIR" and shortwave infrared "SWIR") part of the electromagnetic spectrum, enhances the ability to discriminate and characterise a wide range of natural elements, which, by nature, have different spectral signatures.



This technique is particularly useful for the characterisation of soils according to their various mineral content (e.g. Uranium mines) or the classification of a range of vegetation/crops. Despite a low spatial resolution, the Terra (Aster) and Landsat series are sensors particularly useful for multi-spectral analysis.

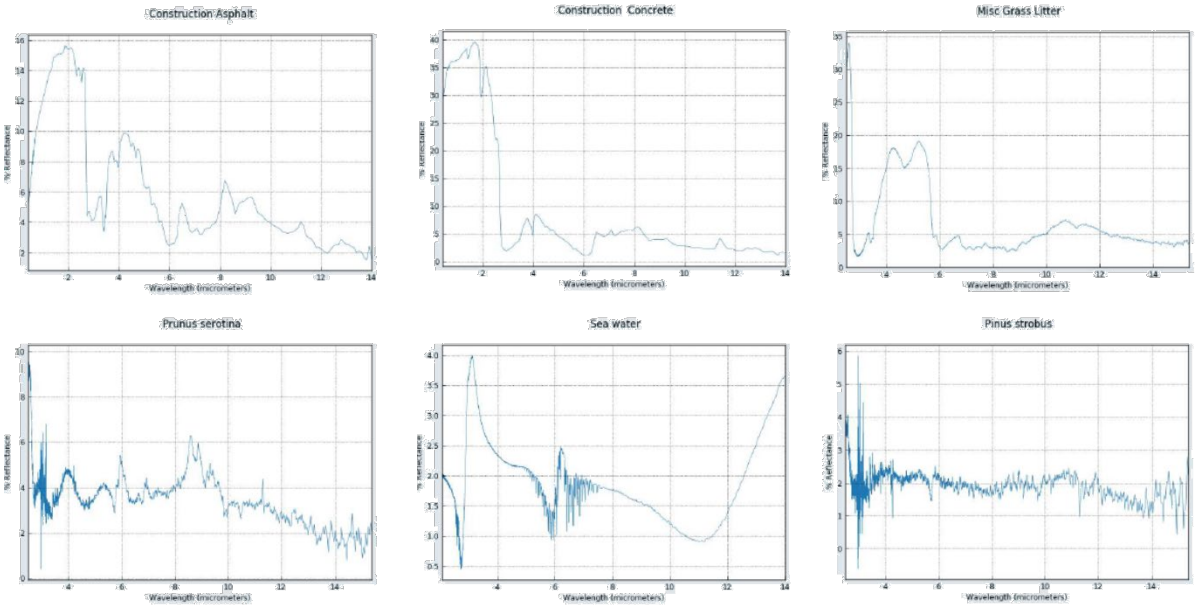


Minerals Composite Indexes
Landsat band ratios of 5/7, 3/1 and 4/3

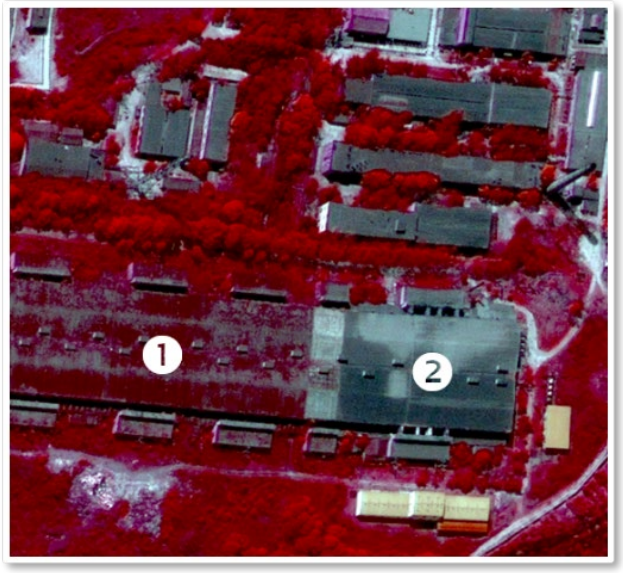


Phosphorite deposits (rocks and dust)
641 composition

Amongst other wavelength bands, all high-resolution multi-spectral sensors provide at least one spectral band in the NIR. NIR is mainly used for the analysis of vegetation stress or diseases by using NDVI[105] techniques. The chlorophyll absorbs visible light for photosynthesis and the structure of the leaves strongly reflects near-infrared light.



The ECOSTRESS spectral library provides a compilation of over 3,500 spectra (spectral signatures) of natural (vegetation and non-photosynthetic vegetation) and man-made materials.



I bands may be used in order to highlight moisture or vegetation on the roof of workshops; an indicator of a derelict status.

For moss to develop, it needs shade and temperatures between 0°C and 22 °C.

❶ *Moss on the roof: derelict status*

❷ *Part of the building well maintained*

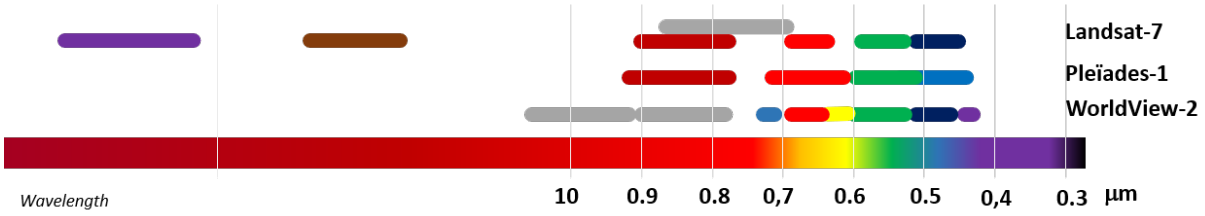
[105] Normalised Difference Vegetation Index

NIR bands support evidence of vegetation stress caused by toxic gas release or fire.

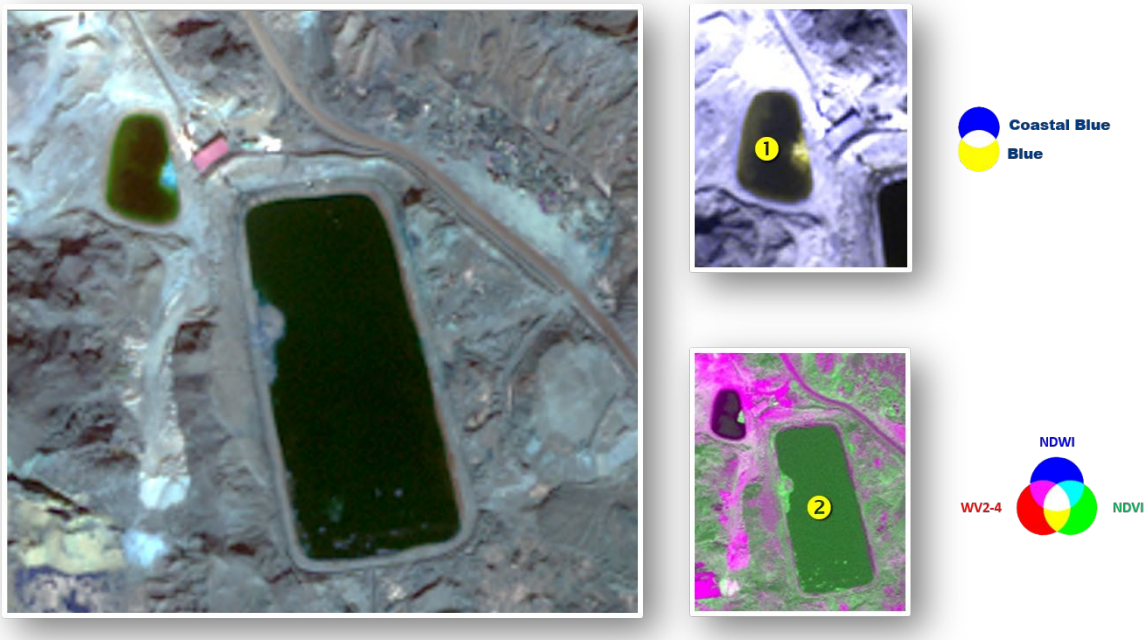
Burned vegetation/trees ❶

Dust on trees canopy ❷

Since October 2009, the Digital-Globe WorldView-2 sensor has provided high-resolution 8-band multispectral imagery.



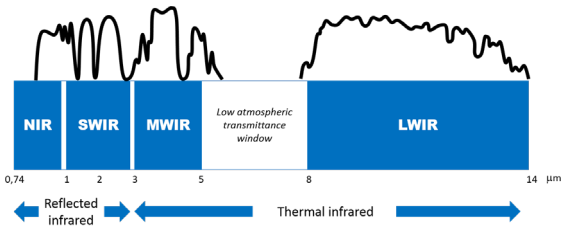
The Red-Edge spectral band (705-745 nm), Coastal Blue band (400-450 nm) or Yellow (585-625 nm) band strengthen analysis capabilities, in particular the discrimination between healthy vegetation and those affected by disease as well as an significant improvement of "bathymetric" measurements.



These spectral bands can also be very useful in determining the density and/or turbidity analysis of liquid ponds

Use of Thermal Data

The infrared (IR) wavelengths of the spectrum lie between 1µm and 14µm and can be further broken down into two sub-domains: the reflected infrared (1µm to 2.5µm) and the thermal infrared, also called TIR (3µm and 14µm). Due to atmospheric absorption windows, TIR is generally measured over two wavelength extents: 3µm - 5µm and 8 µm to 12 µm.



Terra (Aster) and Landsat series (Landsat 7 and 8) space-borne sensors acquire low spatial resolution (100 m, 60 m and 120 m GSD) temperature data between 8 µm and 12 µm.

In remote sensing, the radiance measured (radiant temperature) by thermal radiometers in the TIR are firstly converted into Digital Numbers (DNs) and subsequently to degrees Kelvin (Kinetic heat). The derived estimated surface relative temperature map is a significant asset for the analysis and assessment of various processes within the nuclear fuel cycle.

Thermal map – Landsat 7

It should be noted that information collected over the thermal infrared spectral wavelength can be strongly affected by climate conditions.

Note: The performance of EO thermal sensors can also be described or assessed by the minimum detectable temperature difference (MDTD).

Temporal Resolution

The temporal resolution specifies the revisit frequency of a satellite sensor for a given location. The following scale is commonly used:

- High temporal resolution: < 24 hours to 3 days
- Medium temporal resolution: 4 to 16 days
- Low temporal resolution: > 16 days

High temporal resolution is significantly enhanced by the capability of on-board sensors to point both along and across the satellite track, providing a revisit capability of 1 to 3.5 days, depending on latitude.

Analysis of Multi-Temporal Data

The accuracy of the assessment of a nuclear facility using remote sensing is based mainly on the ability to detect nuclear facilities in the earliest phase of construction. The foundations of the various buildings, the network of underground utility ducts, as well as the internal layout and structure of the main buildings are crucial for the analysis of the facility.

Construction of underground nuclear facility

Subsequently, the monitoring of a nuclear facility is driven mainly by the revisit capability commonly referred to as temporal resolution and the availability of the sensor.

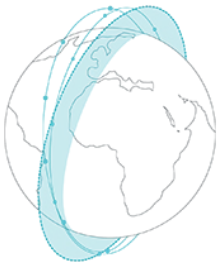
Most of the space-based remote sensing sensors use sun-synchronous (helio-synchronous) nearly-polar orbits. Sun-synchronous orbits ensure the satellite passes over any given point of the earth's surface at the same local mean solar time. Satellite imagery acquired from sun-synchronous orbits provide comparable sun illumination over the years at a given point.

May 2001

May 2004

Temporal resolution of one single satellite depends of the orbit and the altitude of the satellite. Over the last decade, revisit capability has significantly increased thanks to the constellation of satellites.

A constellation is made of two or more satellites. Remote sensing constellations are placed on the same orbit plane but with a different phasing.



Commercial constellations of remote sensing satellites are already available and additional ones are planned for the coming years.

On 14 Feb 2017, Planet, an American private earth imaging company, successfully launched and placed into orbit 88 remote sensing satellites which complemented the 87 already in orbit.

Planet launches satellite constellation to image the whole planet daily.

A total of 300 million km² of imagery are acquired on a daily basis by the constellation, which mainly consists of CubeSats that weigh 4 kilograms and are 10 cm × 10 cm × 30 cm in length, width and height. They orbit at about 400 km and provide imagery with a resolution of 3 to 5 m.

Once the nuclear facility is operating, the analysis of its status from satellite imagery relies on indirect indicators of activity such as vapour plumes, efflux, liquid output, cooling fan rotation, vehicle activity, maintenance activity, damage, etc.

Vapour[106]

Water out-take

Maintenance

The monitoring of infrastructure and the analysis of changes can be visually strengthened by the processing of **anaglyph views**, which formed from two satellite images taken with slightly different angles. The image acquired with the larger incidence is assigned to the red-colour channel while the other image is allocated to the two remaining colour channels. This combination will create the illusion of relief and can be seen using bi-coloured lens glasses commonly red/green or red/blue.

The unprecedented number of remote sensing satellites available significantly eases the monitoring of nuclear facilities on a daily basis.

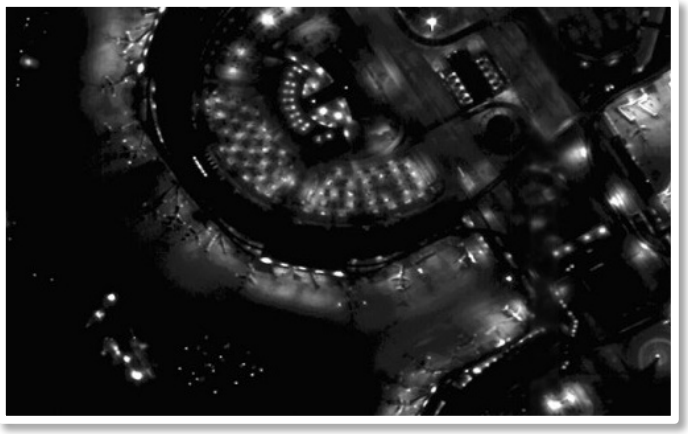
TandemX ; TerraSarX ; RadarSat-2 ; Formosat-2 ; RapidEye-2/3/5 ; RapidEye-5 ; Pleiades-1A ; SuperView-1; SuperView-1 01; Kompsat-3 ; ErosB ; WorldView1 ; RadarSat-2; Sentinel-1A; CosmoSkymed-1/2

[106] The dew point is the temperature at which the air becomes 100% saturated. At that point, the air condenses into water droplets, which we see as fog. Fog forms when the difference between temperature and dew point are ± 15 °C.

Due to different orbital planes, each space-based sensor delivers imagery at a specific local time.

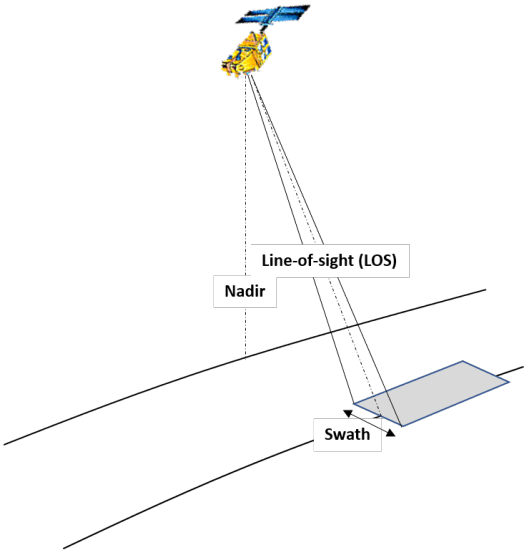
Most space-based sensors acquire imagery during the morning at local time. SAR sensors are capable of acquiring data during both the day and at night.

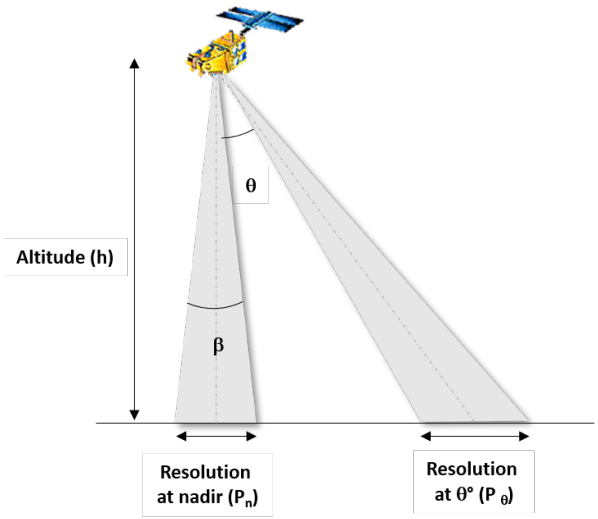
In addition, satellites such as EROS-B (earth resource observation satellites) are capable of acquiring night-time high-resolution satellite images.



In order to improve significantly the revisit capacities, current space borne sensors are capable of moving off the satellite track's nadir.

Sensors equipped with lenses or telescopes require a narrow swath in order to improve spatial resolution. Spatial resolution is commonly inverse to the swath capabilities.





It is noteworthy that the spatial resolution may dramatically decrease when a sensor reaches high off-nadir line-of-sight.

$$P_\theta = \frac{\beta h}{\cos^2\theta} = \frac{P_n}{\cos^2\theta}$$

Simplified formula

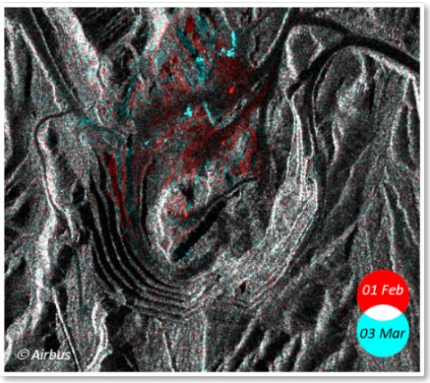
Processing and Analysis of SAR Data

Synthetic Aperture Radar (SAR) is a coherent system. SAR images are comprised of complex data containing both amplitude and phase information.

A series of specific techniques are commonly used by imagery analysts (IAs) to extract information from SAR data.

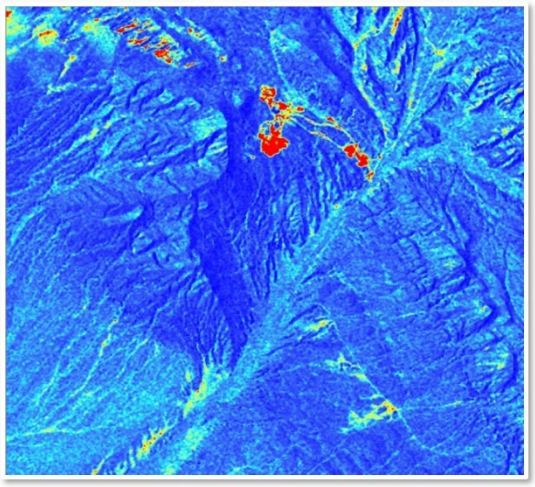
The analysis of single SAR data requires a lot of experience and a good understanding of SAR geometry and phenomenona such as layover, foreshortening, shadowing and texture. The visualisation (display) of the full range of SAR dynamic data is one of the main challenges. IAs routinely uses coloured dynamic look-up tables (LUT) and in particular the rainbow colour display. This coloured image enhances the analysis of high reflected radiation, as well as features that do not reflect any, or very poor, radiation.

The amplitude change detection (ACD) technique consists of comparing at least two examples of SAR data acquired using similar orbit and frequency parameters on different dates. The amplitude data is co-registered before being assigned to the corresponding colour channel (red, green and blue). Thus, changes appear according to the colour synthesis model.



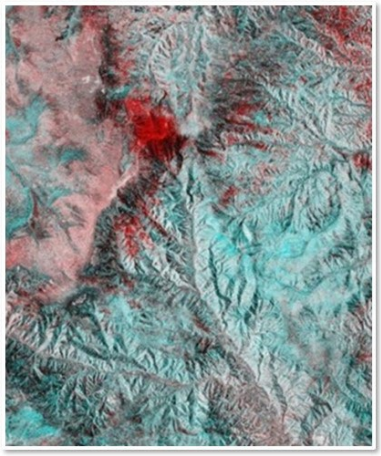
Analysis of amplitude SAR data can support the monitoring of nuclear-related nocturnal activity. However, the analysis derived solely from SAR amplitude imagery can only provide assumptions and therefore requires confirmation by electro-optical analysis.

One of the benefits of SAR systems is coherence. When two or more examples of SAR data were collected along identical orbits with similar acquisition parameters, commonly known as interferometric acquisition conditions, a coherence map derived from the processing of a SAR interferometric pair can be generated. The coherence change detection (CCD) techniques highlight coherence losses mainly due to structural changes between the two acquisition dates. It is particularly relevant for the monitoring and the activity assessment of large uranium mines.



The multi-temporal coherence product combines the two previous techniques. It consists of the combination of two multi-temporal amplitude images and the corresponding computed coherence image. Each image is assigned to one of the colour channels (red, green and blue). The MTC image highlights changes between two states of a target that appeared not to have changed when subject to ACD analysis. This technique is particularly relevant when surveying large storage areas (UO2 or UF6 casks) and often used to complement the CCD technique.

Ground-surface deformation phenomena induced by underground development can be detected using a SAR differential interferometry subsidence map. Subsequent interferograms, formed by patterns of interference between the phase components of two SAR data acquired from the same orbit with slightly different incidence angles and at different times, provides high-density spatial mapping of ground-surface displacements. Under ideal conditions, it is possible to resolve changes in elevation in the order of a few millimetres.



Amongst the differential interferometric techniques, the permanent or persistent scatterer interferometry (PSI) [10] can provide evidence of tunnelling or ongoing underground activity. However, the amount of SAR data required as input to process and produce an accurate and reliable subsidence map, as well as the timeline for the acquisition of the required dataset, means that this technique is not very well suited to time sensitive operational usage. In addition, natural changes due to vegetation or seasonal variation will denigrate the relevant results. Thus, differential multi-pass SAR interferometry (DInSAR) is a technique useful for accurately detecting and estimating the ground displacement or land deformation. In this case, the phases of less SAR data (3 to 5), acquired from slightly different orbital configurations at different times, are combined in order to exploit the phase shift of the signals and compute a surface displacement map.

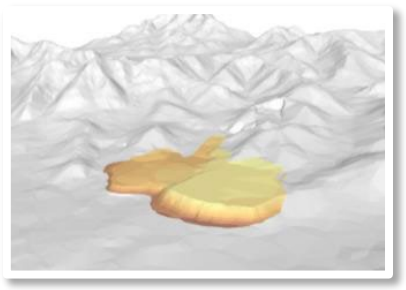
Use of Digital Elevation Model (DEM)

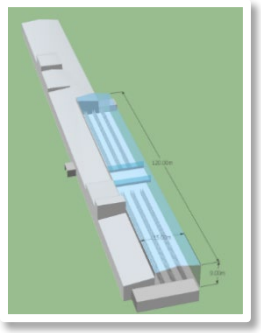
An accurate digital elevation model (DEM) can be obtained from the processing of an interferometric data pair, as well as from an optical stereo-pair, and can be used for the 3D rendering of an optical satellite image. This product provides the IA with enriched contextual insights and a more realistic and natural perspective of the area of interest (AOI).

Anaglyph data requires special glasses

Satellite imagery overlapped on DEM

Furthermore, the difference between two DEMs may also be used to estimate volume variation, in particular in assessing spoil from underground extraction over a specific period





Monitoring data sets, including heterogeneous sensor, viewing angle and season, can also be used to create 3D models. The 3D models derived from satellite imagery provide the analyst with a more realistic contextual view of specific features.

In recent years, challenges and opportunities for satellite imagery analysis have grown dramatically. New very high spatial and spectral resolution sensors with significantly improved revisit times provide unprecedented opportunities to monitor sites and activities.

Data-Mining, Machine Learning and Deep Learning

Since the 1970s, the volume of data collected by space-based remote sensors has grown exponentially. For example, the European Space Agency's (ESA) Sentinel-2 satellite delivers two-and-a-half terabytes[107] of data every day. According to the DLR, 60 petabytes[108] would be needed to safeguard seven years of data from Sentinel-1, 2, and 3's missions.

> By the year 2020, many experts predict the global universe of accessible data to be at the order of 44 trillion gigabytes with no signs of the exponential growth slowing.

The analysis, processing and storage of such an incredible amount of data has become a key issue. Evolving information technologies have efficiently supported the analysis and processing of this massive amount of data. The advent of cloud technology and cheap computing power has opened an unforeseen evolution of new capabilities.

data mining
The practice of examining large pre-existing databases in order to generate new information.

big data
Extremely large data sets that can be analysed by computers to reveal patterns, trends and associations, especially relating to human behaviour and interactions.

Deep Learning – Machine Learning

Machine learning is an application of artificial intelligence (AI) that provides systems with the ability to automatically learn and improve from experience without being explicitly

[107] 1 terabyte = 10^{12} bytes (1012 bytes) = 1,000 gigabytes
[108] 1 petabyte = 10^{15} bytes

programmed. Machine learning focuses on the development of computer programs that can access data and use it learn for themselves.

Several trillion-pixel images of the earth are collected each day by space-based remote-sensors[109]. While this is unprecedented supply of earth observation data, most of it is not being analysed. Information technology (IT) is becoming better every day, especially regarding efficiency. Machines can endorse and carryout repetitive tedious tasks, such as scanning and processing massive quantities of data, freeing humans to focus on complex tasking, validation and assessment.

New technologies based on AI, computer vision and machine-learning enable the processing of such a huge amounts of data to find patterns, trends or anomalies that otherwise might not be found.

Advances in AI algorithms for object recognition and broad-area searches, combined with intelligence information, allow intelligent models for alerting and notification.

Algorithms can also analyse and learn from imagery and location data based on known patterns to help organise and categorise the information analysts need and are most interested in.

Applying cutting-edge AI technology to spatial analytics creates a smarter GEOINT capability, a definite edge.

Turning data into meaning: INSIGHTS and ANALYTICS

Automatic analysis, predicative analysis, trends identification, anomaly detection

QUANTCUBE TECHNOLOGY Orbital Insight SPACEKNOW Picterra

Conclusions and Way Ahead

Although satellite imagery and subsequent remote sensing techniques will never supply all the relevant information required for the assessment of nuclear facilities (such as undeclared facilities), the unprecedented number of available or foreseen space-borne platforms will almost certainly contribute to a more comprehensive analysis capability.

The processing of massive amounts of data collected by the space-borne sensors, supported by the development of innovative/disruptive data analysis methods empowered by new AI technologies, are expected to provide the analyst with new insights.

[109] *skylabanalytics.com*

Nevertheless, strong knowledge and skills will be required to achieve the most valuable synthesis of the full range of information acquired from various parts of the electromagnetic spectrum and the synergy of remote sensing techniques.

In addition to some intrinsic qualities such as curiosity, objectivity and discernment, image analysts have to understand a wide range of sciences ranging from physics, chemistry, optics and forestry, amongst others.

Strategic Trade Control and Nuclear Safeguards

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1 Introduction

Strategic trade controls encompass the broad range of dual-use trade, i.e exports, brokering, technical assistance, transit and transfer of dual-use items, as well as imports, especially for statistical analyses.

Originating from steps undertaken to counter the spread of nuclear weapons following the end of World War II, nuclear export control and nuclear safeguards developed in parallel as two intimately linked elements of the non-proliferation framework. The link is evident in both the Non Proliferation Treaty, entered into force in 1970 [1], and the Nuclear Suppliers Group's (NSG) Trigger List guidelines developed since the mid 70's [2], as it will be explained in the following sections in details.

1.1 The Non-Proliferation Treaty (NPT)

The close relationship between export control and nuclear safeguards is clearly visible in the NPT Article III.2's requirement for safeguards as a principal condition of the supply of nuclear items:

Each State Party to the Treaty undertakes not to provide: (a) source or special fissionable material, or (b) equipment or material especially designed or prepared for the processing, use or production of special fissionable material, to any non-nuclear-weapon State for peaceful purposes, unless the source or special fissionable material shall be subject to the safeguards required by this Article.

The need to interpret the term "especially designed or prepared for" components led to the formation of the NPT Exporters' (or Zangger) Committee [3], which could not come up with a definition but instead identified a list of key nuclear fuel cycle items.

In 1974 the resulting Zangger Committee's "Trigger List" (i.e. a list of equipment and facilities "triggering" the need for safeguards) and guidelines for the supply were communicated to Member States by the IAEA in INFCIRC/209.

1.2 The Nuclear Suppliers Group (NSG)

The Indian "peaceful nuclear explosion", in 1974 showed however that, notwithstanding the entry into force of the Non Proliferation Treaty, various countries had anyway exported nuclear goods and technology to India, a non-signatory to the Treaty.

The "Nuclear Suppliers Group (NSG)" [4] was therefore formed in 1974 to include also some non-NPT signatory countries, which could not be part of the Zangger Committee. The NSG also issued its "Guidelines for nuclear transfers" in 1975, including an extended Trigger List, published as INFCIRC/254/Part 1 [2].

These first NSG guidelines, meanwhile updated 14 times, set nuclear safeguards as a condition of supply for nuclear items (i.a. also together physical protection requirements) and include two annexes, of which Annex B contains the Trigger List (TL).

The creation of a second set of NSG guidelines covering "dual-use" equipment was decided in 1992, as a consequence of the discovery of the covert Iraqi nuclear programme, which could be developed also relying on the illicit import of goods and technology non "especially designed of prepared for nuclear use".

The resulting NSG "Guidelines for transfers of nuclear-related dual-use equipment, materials, software and related technology", contain in annex the actual NSG Dual-Use List (DUL) [5].

These developments marked the beginning of a constant evolution of nuclear export controls in relation to nuclear safeguards following the international events and crises.

With the exception of the 1978-1991 period, the NSG has been quite active since its establishment, growing its membership to the current 48 Participating Governments, plus the European Commission as observer.

The two distinct NSG guidelines and their Annexes are described in the next section:

2 Contents of the NSG GUIDELINES

2.1 Guidelines for Nuclear Transfers: The Trigger List (INFCIRC 254/Part 1)

The NSG Part 1, or Trigger List, guidelines (NSG TL, [2]) describe the various elements of the "Non-Proliferation principle", i.e. the synergy among nuclear safeguards, export control and physical protection.

The actual *NSG Trigger List* is included as attachment (Annex B, see below).

The NSG guidelines for nuclear transfers include the following list of sections and annexes:

- Prohibition on nuclear explosives
- Physical protection
- Safeguards
- Special controls on sensitive exports (enrichment and reprocessing)
- Special arrangements for export of enrichment facilities, equipment and technology
- Controls on supplied or derived material usable for nuclear weapons or other nuclear explosive devices
- Controls on retransfer
- Non-proliferation Principle
- Implementation

SUPPORTING ACTIVITIES

- Support for access to nuclear material for peaceful uses
- Physical security
- Support for effective IAEA safeguards
- Trigger list plant design features
- Export Controls
- Consultations

ANNEX A – TRIGGER LIST REFERRED TO IN GUIDELINES

- GENERAL NOTES
- TECHNOLOGY CONTROLS
- SOFTWARE CONTROLS
- DEFINITIONS

MATERIAL AND EQUIPMENT

1. Source and special fissionable material
2. Equipment and Non-Nuclear Materials (*i.e. Trigger List's headings*)

ANNEX B

CLARIFICATION OF ITEMS ON THE TRIGGER LIST

1. Nuclear reactors and especially designed or prepared equipment and components therefor;
2. Non-nuclear materials for reactors;
3. Plants for the reprocessing of irradiated fuel elements, and equipment especially designed or prepared therefor;
4. Plants for the fabrication of nuclear reactor fuel elements, and equipment especially designed or prepared therefor;
5. Plants for the separation of isotopes of natural uranium, depleted uranium or special fissionable material and equipment, other than analytical instruments, especially designed or prepared therefor;
6. Plants for the production or concentration of heavy water, deuterium and deuterium compounds and equipment especially designed or prepared therefor;
7. Plants for the conversion of uranium and plutonium for use in the fabrication of fuel elements and the separation of uranium isotopes, and equipment especially designed or prepared therefor

2.2 Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Materials, Software, and Related Technologies

The NSG DUAL USE LIST (NSG DUL, [5]), published by IAEA as INFCIRC 254/Part 2, contains more extensive recommendations on the export control framework and procedures, as well as in Annex the list of items not especially designed or prepared for nuclear use, but equivalent to those needed to develop Trigger List systems and components.

The detailed structure of the NSG DUL is the following:

- OBJECTIVE
- BASIC PRINCIPLE
- EXPLANATION OF TERMS
- ESTABLISHMENT OF EXPORT LICENSING PROCEDURES

- CONDITIONS FOR TRANSFERS
- CONSENT RIGHTS OVER RETRANSFERS
- CONCLUDING PROVISIONS

The list of dual-use items is reported in its ANNEX: LIST OF NUCLEAR-RELATED DUAL-USE EQUIPMENT, MATERIALS, SOFTWARE, AND RELATED TECHNOLOGY, together with general notes and definitions and structured as follows:

- INDUSTRIAL EQUIPMENT
- MATERIALS
- URANIUM ISOTOPE SEPARATION EQUIPMENT AND COMPONENTS
- HEAVY WATER PRODUCTION PLANT RELATED EQUIPMENT
- TEST AND MEASUREMENT EQUIPMENT FOR THE DEVELOPMENT OF NUCLEAR EXPLOSIVE DEVICES
- COMPONENTS FOR NUCLEAR EXPLOSIVE DEVICES

2.3 Comments and Observations

All together, the two lists cover the nuclear fuel cycle and weaponisation segments, including the materials and the industrial equipment needed to produce the necessary parts. See Figure 1.

While the NSG Trigger List refers to export controls on equipment, facilities and materials subject to nuclear safeguards, the NSG DUL contains industrial equipment, materials and additional "dual-use" items instrumental to the nuclear fuel cycle segments described by the NSG Trigger List, with the addition of the weaponisation segment, marked in red in Figure 1.

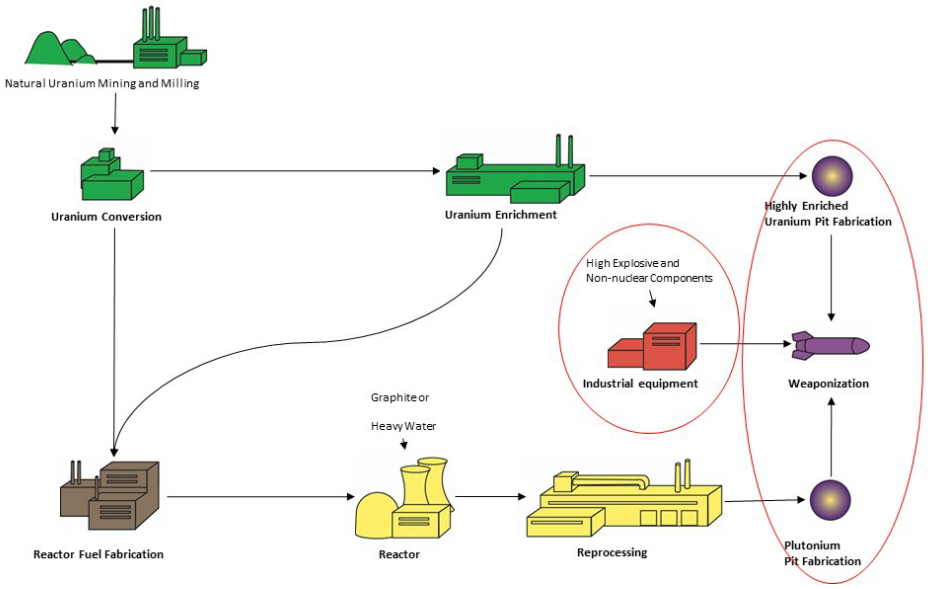

Figure 1 – A schematic on the nuclear fuel cycle's segments, plus weaponisation and industrial equipment as foreseen in the NSG guidelines.

3 Evolution of the International Safeguards Framework

The discovery of undeclared proliferation activities in Iraq in 1991 was a turning point also for what concerns the international safeguards framework.

The implementation of a Comprehensive Safeguards Agreement (CSA) with a focus on declared nuclear material at declared facilities did not prove to be sufficient to prevent the development of the Iraqi military nuclear programme in the 1990s. This led the IAEA and its Member States to start a paradigm shift for the implementation of NPT safeguards, from both a legal and practical point of view.

From a legal point of view, the introduction in 1997 of the "Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards" (AP - INFCIRC/540) [6] expanded the set of information that the State is required to transmit to the Agency under their reporting obligations. It also expanded the verification toolkit at the IAEA disposal to exclude the presence of possible undeclared nuclear material and activities in a State.

3.1 Model Additional Protocol's Requirements in Relation to Export Control and Research

The Model Additional Protocol's Article 2.a. requires that States provide a series of data and pieces of information that allows the agency to consolidate its vision about the nuclear fuel cycle's development in countries. Not surprisingly, this information is quite directly linked to the NSG lists.

To begin with, States are called to provide the Agency with a declaration containing:

(i) A general description of and information specifying the location

of nuclear fuel cycle-related research and development activities

not involving nuclear material

Art. 2.a.(i) allows the IAEA to identify those research activities, which carry out potentially sensitive and relevant research, which could be transferred "intangibly" violating the export control provisions (Intangible Transfers of Technology).

These R&D sites would not appear in the declarations linked to the actual presence of nuclear material and therefore could not be captured by the requirement of Art. 2.a.(i).

Art. 2.a. (iv) instead calls on States to provide: "A description of the scale of operations for each location engaged in the activities specified in Annex I to this Protocol".

3.2.1 Model Additional Protocol's Annex I

Annex I lists fifteen key nuclear fuel cycle (NFC) related activities, as follows:

i. The manufacture of *centrifuge rotor tubes* or the assembly of *gas centrifuges*.
ii. The manufacture of *diffusion barriers*.
iii. The manufacture or assembly of *laser-based systems*.
iv. The manufacture or assembly of electromagnetic isotope separators.
v. The manufacture or assembly of *columns* or *extraction equipment*.
vi. The manufacture of aerodynamic separation nozzles or vortex tubes.
vii. The manufacture or assembly of uranium plasma generation systems.

viii. The manufacture of *zirconium tubes*.

ix. The manufacture or upgrading of *heavy water or deuterium*.

x. The manufacture of nuclear grade graphite.

xi. The manufacture of flasks for irradiated fuel.

xii. The manufacture of *reactor control rods*.

xiii. The manufacture of criticality safe tanks and vessels.

xiv. The manufacture of irradiated fuel element chopping machines.

xv. The construction of *hot cells*.

These activities are instrumental to the segments represented in Figure 1 which can be summarised as follows:

- Enrichment, or isotope separation: Activities i. – vii
- Nuclear reactors: Activities viii – x and xi
- Reprocessing: Activities x – xv (excl. xi)

3.2.2 Model Additional Protocol's Annex II

The Model Additional Protocol also foresees the provision to IAEA of export declarations of "Trigger list" items listed in its Annex II.

Art. 2.a.(ix) indeed requires that States:

…shall provide the Agency with a declaration containing the following information regarding specified equipment and non-nuclear material listed in Annex II:

For each export: the identity, quantity, location of intended use in the receiving State and date … of export;

Upon specific request, confirmation as importing State of information provided by another State concerning the export of such equipment and material

Annex II lists the items contained in the NSG Trigger List (INFCIRC 254/Part 1) available in 1995 (Rev. 2), with the exception of "technology" and "software" which are not included, similarly to the Zangger Committee's Trigger List. An analysis of the importance and extent to which technology controls are anyway due to be declared is reported in [7].

Unfortunately, the AP Annex II list has not been amended since 1997, as it would have been necessary to do to follow the evolution of the NSG Trigger List, whose latest version is Rev. 14 of 2019. This fact creates discrepancies to exporters and authorities which are addressed in various practical ways as outlined in [8, 9].

Table 1 summarises the items part of the NSG Trigger List (Annex B of INFCIRC/254 Part 1, as of Revision 14 of 2019), which are not included in Annex II of the Additional Protocol (INFCIRC/540c), with their year and revision of appearance in the Trigger List. The table does not contain items that have simply been the object of editorial improvements.

Table 1: Summary of items part of the NSG Trigger List.

Annex B item	Title	Since	Year
1.8	Nuclear reactor internals[110]	Rev. 3	1997
1.9	Heat exchangers	Rev. 3	1997
1.10	Neutron detectors	Rev. 3	1997
1.11	External thermal shields	Rev. 12	2013
3.5	Neutron measurement systems for process control	Rev. 12	2013
5.2.1.c	Solidification or liquefaction stations	Rev. 12	2013
5.2.3	Special shut-off and control valves	Rev. 9	2007
6.8	Complete heavy water upgrade systems or columns therefor	Rev. 3	1997
6.9	NH_3 synthesis converters or synthesis units	Rev. 12	2013
7.1.9	Especially designed or prepared systems for the conversion of UO_2 to UCl_4	Rev. 4	2000

The States or other organizations depending on the countries' attribution of competences (e.g. EURATOM for some European Union Member States), are responsible for retrieving AP-related information and provide it to the IAEA along with the CSA-related and other required declarations.

The experience of some ESARDA members with the activities and export declaration provisions of the AP are summarised in [10].

4. From Nuclear Export Control to Strategic Trade Control: The International Export Control Regimes and Other Relevant Treaties

The NSG guidelines are probably the element of the export control framework most known to nuclear safeguards experts, but it may be interesting also to get a short overview of the other non-nuclear regimes and treaties, which contribute to the overall trade control legal and technical architecture.

Indeed, given the increasing relevance of other types of Weapons of Mass Destruction (WMD), the NSG was followed in the 80's by the establishment of the Australia Group (AG, 1985 [12]), the Missile Technology Control Regime (MTCR, 1987 [11]) and later by the Wassenaar Arrangement (WA, 1996, [13]), with their respective control lists.

[110] Only mentioned in the Explanatory Note to item 1.2 (Reactor pressure vessels) in Annex II of the Additional Protocol

Australia Group (AG)

The AG was set up in 1985 and currently has a broad membership of 42 Participating Governments, including all the European Union Member States and the EU itself.

The AG defines Common Control Lists for:

- Chemical Weapons Precursors
- Dual-use chemical manufacturing facilities and equipment and related technology and software
- Dual-use biological equipment and related technology and software
- Biological agents
- Plant pathogens
- Animal pathogens

Missile Technology Control Regime (MTCR)

The MTCR, established in 1987, has a more limited participation of 35 governments, not including eight EU Member States and the EU itself. Its mission is to coordinate national export licensing efforts aimed at preventing proliferation of unmanned delivery systems capable of delivering weapons of mass destruction.

The MTCR defines the following controls:

- Category I: Complete ballistic and cruise missiles with range greater than 300 km and payload greater than 500 kg-Major subsystems such as: engines, guidance sets, space launch vehicles, sounding rockets, and unmanned aerial vehicles (UAVs)
- Category II: Items needed to construct Category 1 systems and non-Category I systems

Wassenaar Arrangement (WA)

The Wassenaar Arrangement was established in 1996 after the end of the Coordinating Committee (COCOM) [14], to define a comprehensive list of dual-use addressing the overall WMD threat (nuclear, biological, chemical and delivery means), which forms the broader dual-use list available, as well as the conventional arms controls list, which is the basis of the Munition List of various countries. The WA also publishes a number of Best practice guidelines. This regime currently has 41 participating governments.

Other Treaties and agreements

Other international treaties are linked to non-proliferation and disarmament by targeting weapons of mass destruction.

The Biological Toxin Weapons Convention

This treaty entered into force in 1975, with 183 signatory State Parties as of March 2022 [15].

The Chemical Weapons Convention

Entered into force in 1992, this treaty requiring States to ban chemical weapons and allow inspections to chemical plants, includes requirements for disarmament as well as inspections of precursors' production.

The CWC has so far been subscribed by 193 countries and contains three Schedules (or lists) of chemical weapons and precursors subject to inspections and verification by the Organisation for the Prohibition of Chemical Weapons (OPCW) [16].

5 Control Lists and the General Strategic Trade Control Framework

Strategic trade control is a barrier against proliferation called for by the United Nations Security Council Resolution 1540 [17], aiming to limit the unauthorized access of states and sub-national entities to strategic technology and goods.

The lists defined by the international export control regimes and many elements of the associated guidelines are the building elements of the overall strategic trade control framework. This applies not only to the relatively limited number of countries participating in the regimes (e.g. 48 in the NSG), but also to many others who wish to be part of the global supply chain which requires due diligence in managing sensitive imports, exports and re-exports of tangible goods, as well as of technology and software containing the know-how.

Taking the example of the EU, the Dual-use Regulation 2021/821 [18] includes as Annex I the so-called *European Union "dual-use control list"*, resulting from a large effort carried out in the mid 90's to integrate into one single control list all the lists defined by the WA, MTCR, NSG and AG international export control regimes, complemented by the chemical precursors included in the Chemical Weapons Convention.

The dual-use control list is organised into 10 categories, respectively as follows:

- Category 0: "Nuclear Materials, Facilities and Equipment", including:
    - Plants for the separation of isotopes of natural uranium, depleted uranium
    - Auxiliary systems for isotope separation plants
    - Plants for conversion of uranium
    - Plants for heavy water production
    - Plants for nuclear reactor fuel element fabrication
    - Plants for the reprocessing of irradiated fuel elements
    - Plants for the conversion of plutonium
- Category 1: "Special Materials and Related Equipment";
- Category 2: "Material processing";
- Category 3: "Electronics";
- Category 4: "Computers";
- Category 5 Part 1: "Telecommunications";
- Category 5 Part 2: "Information Security";

- Category 6: “Sensors and Lasers”;
- Category 7: “Navigation and Avionics”;
- Category 8: “Marine”;
- Category 9: “Aerospace and Propulsion”.

The canvas of the control list’s structure derives from the Wassenaar Arrangement. As it is easy to realise, Category 0 of the EU dual-use control list corresponds to the NSG Trigger List of items *“especially designed or prepared for the processing, use or production of special fissionable materials”*. The NSG Dual-Use List’s items are instead contained in categories 1, 2, 3 and 6. Items from the other regimes are integrated into the various categories minimising duplications, which however still remain (e.g. frequency changers, pressure transducers, machine tools) depending on the parameters or the intended use.

The EU “dual-use control list” is annually amended under a European Commission Delegated Act, whose latest version has been published in 2022 [19]. Besides the EU, the list is used by various countries in the world and it has constituted also the initial model of other national control lists, e.g. the US Commerce Control List (CCL).

Suppliers are obliged to obtain export authorisations for all the items contained in the list, providing information about the end user and the intended end use. In case of Trigger List’s exports, also government-to-government assurances are required to exclude that the export contributes to undeclared nuclear programmes.

Certain United Nations Security Council's and national sanctions measures also include dual-use items’ controls, or even foresee complete prohibitions to the export of the entire dual-use control list of items to specific countries; e.g. see the EU measures targeting Syria, DPRK and the Russian Federation.

On top of the controls related to the actual dual-use control list, the authorities may impose a “catch-all clause” also on goods not specifically listed, if their features can make them anyway instrumental to a proliferation programme. This is the case of technologies considered “emerging” albeit not yet subject to export controls [20].

6 Strategic Trade Control Related Sources of Information

The IAEA does not implement export controls, but benefits from their existence. The strategic export control framework not only provides an important barrier to proliferation, it also helps generating data instrumental to the verification process.

Besides the data formally due by States and collected during regular inspection activities, the IAEA makes wide use of various sources of information to detect potential indicators of undeclared nuclear material and activities, and for States with an AP in force, be able to derive broader conclusions on the absence of undeclared nuclear material and activities.

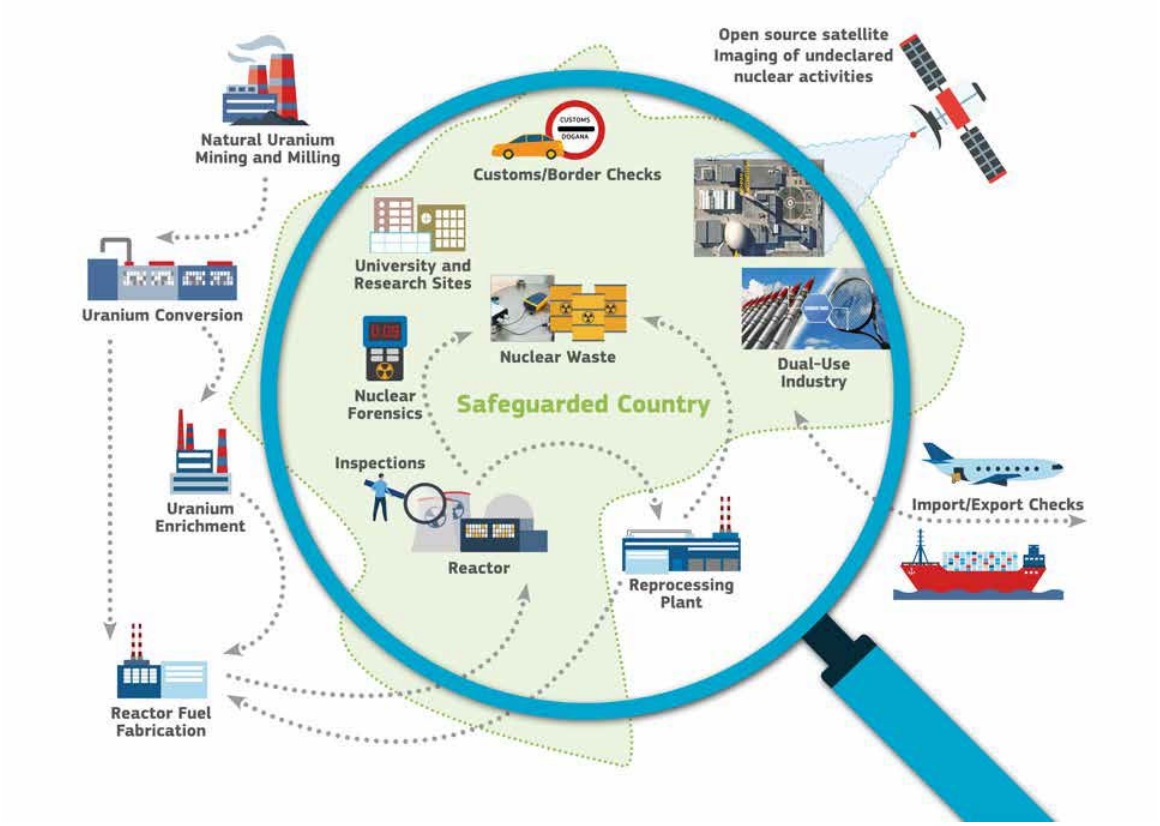

Figure 2 – Matching State's declarations and verification activities [7].

7 Conclusions

The chapter revisited the parallel evolution of international nuclear safeguards and export controls, underscoring once more their close and complementary relationship, which should be continuously reinforced in order to more efficiently counter nuclear proliferation in violation of the NPT.

Details and references of the Nuclear Suppliers Group's guidelines are provided, with a view to show their importance and relevance to the implementation of legal requirements and safeguards provisions, including references to the Model Additional Protocol's annexes.

In the framework of the Model Additional Protocol (AP), the information exchanged with the IAEA includes also the actual exports of nuclear items. Additionally, the IAEA has arrangements with some States to exchange information about refused export control licenses. This provides the IAEA with the possibility to detect at an earlier stage illicit trafficking networks. However, monitoring technology transfers by intangible means poses its own set of problems.

The reporting requirements to IAEA do not cover the supply of Trigger List's technology (= know-how) or software, as there are no physical exports, nor customs declarations to complete. States may anyway report also such transfers, where they are known, on a voluntary basis.

For completeness of information, brief references were made also to the non-nuclear related control which complete the strategic trade control framework.

The overall control of strategic trade is requested by UNSCR 1540 from all the UN members, including those non actually participating in any international export control regime. It is a measure key to both the non-proliferation prevention efforts and the verification of the absence of undeclared activities, as well as an important geo-political and geo-economic instrument.

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The Utility of Open-Sources, Including Commercial Satellite Imagery, for IAEA Safeguards and Non-Proliferation Monitoring and Verification Applications

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Abstract

This chapter focuses on the utility of open sources, in particular openly available commercial satellite imagery, for nuclear safeguards and non-proliferation monitoring and verification applications. Openly available information provides a remote and non-intrusive means to potentially derive relevant insights regarding nuclear facilities, equipment, and activities anywhere on Earth and in some cases, may provide the first clues of illicit activities. The International Atomic Energy Agency (IAEA) has incorporated these previously non-traditional information sources into its nuclear safeguards toolkit and proven them to be an effective way to enhance the IAEA's capabilities for not only monitoring and verification, but also for inspection planning purposes. This chapter reviews, through the use of some instructive exemplars, the ways that these openly available data and tools have helped in that role with a focus on commercial satellite imagery. The chapter also reviews the significant improvements in the capabilities of these data and tools over the past decade, together with some implications that they hold for future non-proliferation applications.

Introduction

The revelation of Iraq's clandestine nuclear weapons program in the 1990s first made clear the necessity of bringing new data sources and tools to bear in the service of the IAEA and other international nonproliferation efforts. That program "*exposed all too clearly the limitations of a safeguards system focused exclusively on declared nuclear material*" [1] and which was only focused upon declared nuclear sites. The adoption in 1997 of the Additional Protocol [2] by the IAEA Board of Governors led to the "Strengthened Safeguards System" under which IAEA began to adopt new measures "*to provide stronger assurances regarding both the non-diversion or misuse of declared nuclear material and the absence of undeclared nuclear activities.*" [3]. The improved system sought to ensure both the completeness, as well as the correctness, of state declarations of their activities. The IAEA's quest for such increased transparency continues to evolve with the adoption of additional sources of information. "*The IAEA makes use of all information including, inter alia, official declarations by the State, information collected during safeguards verification activities, third party, and* ***open source information***. [emphasis added]" [4] Open source information can be defined as "*publicly available information that anyone can lawfully obtain by request, purchase, or observation*" [5]. For its purposes, the IAEA defines open source information specifically as "*information generally available from external sources, such as scientific literature, official information, information issued by public organizations, commercial companies and the news media, and commercial satellite imagery"* [6] as well as analysis of trade data [7].

One result of the Iraq revelations and the consequent introduction of the Additional Protocol was an increased focus on what became known as the State Level Concept, in which "*the International Atomic Energy Agency (IAEA) envisions an objective-based and information-driven approach for designing and implementing State Level Approaches (SLAs)* [8]. "*The main objectives of a SLA are: a) to detect undeclared nuclear material or*

activities in the State, b) to detect undeclared production or processing of nuclear materials in declared facilities or locations outside facilities (LOFs), and c) to detect diversion of declared nuclear material in declared facilities or LOFs." [8]. Such a holistic approach, in which all the information gathered is analyzed and assessed as a whole, is understood to be adaptive, and continuously tested, for its effectiveness against an array of differing, creative, and adaptive proliferators [9].

In an effort to expand the safeguards toolkit, the IAEA (along with other treaty monitoring and verification organizations) recognized that "*ubiquitous information access and widespread observational tools are increasing inherent transparency*" [10] such that they could be enlisted to provide a broader perspective beyond declared material and activities.

There are four key areas of IAEA open source analytical interest [8]:

1) Technical/Scientific official information analysis: scientific literature, official reporting, information issued by public organizations, commercial companies;
2) Media monitoring: news, and social networks;
3) Imagery analysis: commercial satellite imagery, ground-level imagery;
4) Import/export analysis: trade data, legal/illicit procurement information.

This discussion will focus primarily on the contributions of the first three key areas of IAEA interest for safeguards implementation, including comprehensive State Evaluations, with the last being left as a separate subject of study by others. The examples of sources of information and their related analysis reported in this overview are not meant to be exhaustive, but illustrations of the concepts outlined in the related paragraphs.

Open Source Data and Analysis

Open source data fulfills three essential roles in augmenting "all-source" information:

1) Open source data can **corroborate and validate** information obtained through other available sources and methods (as a "second witness") to increase analytic confidence and enhance overall understanding of an issue,
2) Open source data can be **more readily shared** without compromising more sensitive sources and methods, and
3) Open source data has the potential to be the sole-source of information that raises the first "**red flag**" to cue additional resources for the necessary and appropriate follow-up of a previously unknown issue.

With regards to IAEA Safeguards applications, "part 1" measures, implemented under the existing legal authority provided for within Comprehensive Safeguards Agreements, allow the IAEA, *inter alia,* to evaluate open-source information (including satellite imagery) as part of the safeguards process [11]. Open Source information includes (but is not limited to) publicly available information (found on the internet or provided by NGOs, companies, the news media, and governments). It also includes "fee-based" information such as published scientific and technical literature or subscription databases, maps, guidebooks, statistical compilations of data, and textbooks. Other open source information, normally only made available on request or to specific individuals, includes: company financial reports, conference proceedings (participant lists or paper titles, abstracts, or full text), internal publications of various organizations, internal travel reports, technical cooperation summaries, unpublished scientific papers and pre-prints, and patent applications.

In view of the holistic system approach of the State Level Concept, it has also been stated that, "*…open source analysis could be seen as a process of 'getting the right information (what) to the right people (who) at the right time (when) for the right purpose (why) in the right forum (where) and in the right way (how)' by merging openly available data and information coming from a wide variety of accessible sources into an overall comprehensive and cohesive picture. Usually the process involves the gathering and analysis of a large amount of data and information, a very small percentage of it being relevant. A common scenario involves filtering an enormous amount of data to end up with a sparse and incomplete set of information not all of which contributes to knowledge. When investigating a covert military engineering programme, the analyst will have to deal with low quality data and is always exposed to deliberate deception. Nonetheless, the analyst may be able to obtain valuable insights about what a State might be pursuing.*" [12].

Interestingly, with regard to gaining insights on a state's activities, the United Nations recently displayed novel use of open source information and imagery to monitor Iran's compliance with its obligations pursuant to the Joint Comprehensive Plan of Action (JCPOA) pursuant to UN Security Council Resolution 2231 (2015). United Nations analysts found evidence that an Iranian defense organization and an Iranian Major General had been present in Iraq in contravention of provisions of that UNSC resolution. Among the open sources employed included the *Wayback Machine Internet Archive*[111], which the analysts used to recover critical photographs that had been previously deleted from Iranian media websites [13].

Technical/Scientific Publications Can Provide Tip-Offs

A wide variety of information is available through official publications, academic and technical journals, and other media from which to glean insights on not just the capabilities of a nation-state, but also the direction of research and development along the varied paths to nuclear proliferation. There have been several examples where the analysis of scientific and technical journal articles published by governmental institutes, academia, or found within commercial media have provided critical information necessary to discover undeclared, and hence illicit nuclear activities. In this section we will review two examples.

Open-Source Derived Evidence of Undeclared Atomic Vapor Laser Isotope Separation by the Republic of Korea

Open source information played a critical role in the discovery of evidence that the Republic of Korea (ROK) had been engaged in undeclared nuclear activities that had uranium enrichment relevance that require reporting under ROK's safeguards obligations under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). ROK publications suggested to IAEA analysts that ROK scientists had been engaged in Atomic Vapor Laser Isotope Separation (AVLIS), which led to IAEA investigative follow-up. Subsequently, in 2004, the IAEA reported that "*the ROK informed the Agency that, on a number of occasions in the past, experiments which involved uranium conversion and enrichment had been conducted. Earlier in 2004, the ROK had acknowledged, in response to Agency's enquiry, that a laboratory scale experiment had been conducted in the early 80s to irradiate a mini-fuel assembly and to study the separation of uranium and plutonium. These activities had not been previously reported to the Agency as required under the comprehensive safeguards agreement.*" [14].

On August 17, 2004, "*the Korean Ministry of Science and Technology (MOST) reported to the IAEA that ROK had conducted experiments to enrich uranium, extract plutonium, and had produced uranium metal." The*

[111] http://archive.org/web/web.php

ROK's Laboratory for Quantum Optics at KAERI conducted experiments to enrich uranium three times during January and February 2000. The experiments were conducted using atomic vapor laser isotope separation (AVLIS) and yielded about 0.2 grams of uranium enriched to an average of 10 percent in the three experiments. The peak level of enrichment in the experiments was 77 percent." [15]. Korean scientists separated uranium-235. The Korean Atomic Energy Research Institute (KAERI) had published over a dozen papers on the spectroscopy of uranium and uranium compounds between 1991-2004, most of which involved the same research team. Many were published in Optics Communications in 1993, 1994, 1998, and 1999 [16].

Open-Source Derived Evidence of Undeclared Plutonium Separation Relevant Activities by Egypt

Open source information played a critical role in the discovery of evidence that Egypt had been engaged in undeclared nuclear activities relevant to plutonium separation that should have been reported under Egypt's safeguards obligations under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). Publications by Egyptian scientists suggested that they had been engaged in clandestine uranium conversion and reprocessing activities, which led to subsequent IAEA enquiry. In 2004, the IAEA reported that "*During the preparation of the State evaluation update for Egypt in 2004, the Agency noted a number of* ***open source*** [emphasis added] *documents that indicated the possibility of unreported nuclear material, activities and facilities in Egypt. In December 2004, Egypt acknowledged that between 1990 and 2003 it has conducted experiments, which had not previously been reported to the Agency, involving the irradiation of small amounts of uranium and thorium and their subsequent dissolution. Egypt also acknowledged that it had failed to include laboratories and some imported and domestically produced nuclear material in its initial declaration.*" [14]. Had it not been for the tip-off provided by open source information, the activities that were labeled by the IAEA as, "a matter of concern," might never have been discovered [17].

Open Source Media Reporting Can Provide Unexpected Insights

Open Source Information can be found via various blogs that have particular areas of interest relevant to treaty monitoring and verification organizations. In the case of North Korea, there are a number of websites with such potential, of which many are in English[112] (and more in other languages such as Korean, Mandarin, etc.). The following is an example where an unexpected insight was obtained, which, while not safeguards relevant is nonetheless of non-proliferation interest, pertains to North Korean nuclear weapons testing and containment techniques.

On September 8, 2010, Pyongyang Korean Central Television broadcast a partially animated dramatization purportedly related to its 2009 underground nuclear test. Several of the graphics from that video surfaced on North Korea-focused blogs, with one graphic including an alleged layout of the test tunnel as depicted in the center of Figure 1. [113] The tunnel layout appears to have engineering features similar to descriptions of the tunnel involved in the 1998 Pakistani underground nuclear test. It includes several flat S-shape and zigzag features, and a loop-around hook (e.g., "fishhook") leading to the device emplacement chamber [18]. France reportedly employed a similar hook feature during its underground nuclear tests in Algeria during the 1960s. [19] While it must be recognized that the information published in a blog derived from a state-sponsored propaganda video must be viewed skeptically, some engineering features were nonetheless found to be consistent with underground testing and containment practices.

[112] See for example: http://38north.org/, http://www.northkoreatech.org/, http://www.nkeconwatch.com/, http://freekorea.us/, http://nkleadershipwatch.wordpress.com

[113] https://nkleadershipwatch.files.wordpress.com/2012/06/tctis_f_xop.jpg

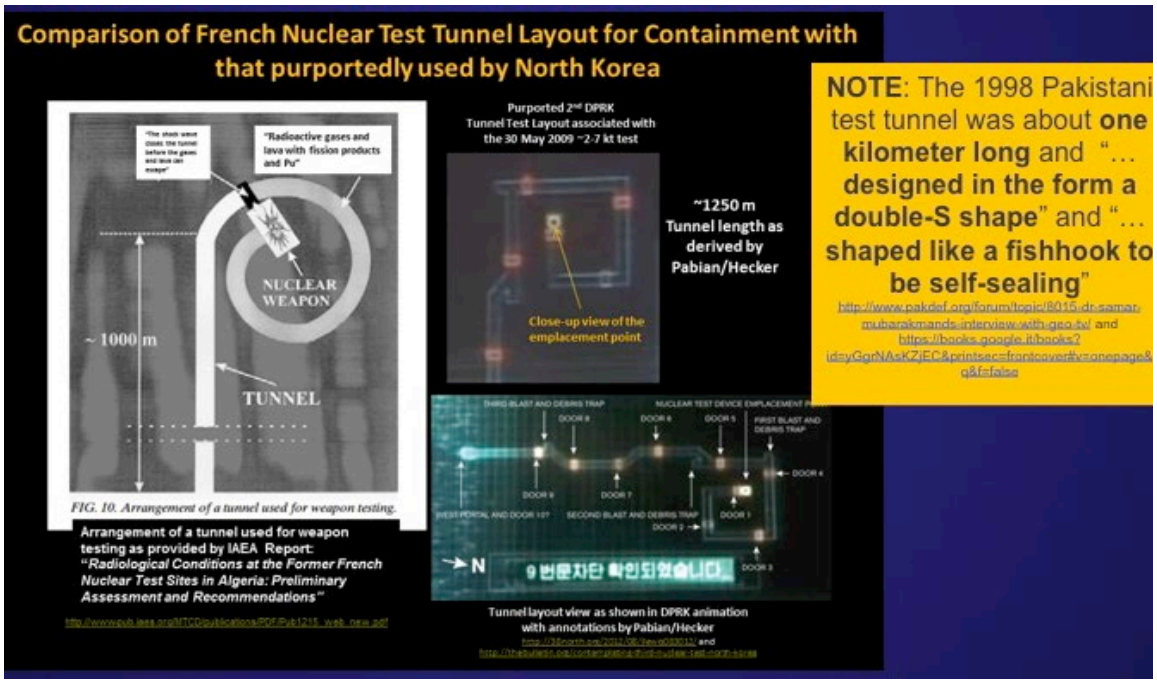

Figure 1: Open source information can provide insights on possible tunnel design and containment engineering.

Commercial Satellite Imagery: A Valuable Open Source Tool[114]

Commercial satellite imagery has, since the turn of the new millennium, become an increasingly valuable open source for IAEA Safeguards purposes. [20] Moreover, "*satellite imagery is used routinely to evaluate information provided by States on their nuclear activities and to plan inspections, visits to facilities to verify design information and to conduct complementary access under the Additional Protocol.*" [11] The IAEA has also stated, "*For monitoring purposes, imagery obtained by commercial satellite imaging sensors can greatly help inspectors track activities.*" [21] Medium resolution (e.g., one to two meters) imagery "*provides the ability to perform broad area searches in instances where exact location may not exist, to very high resolution imagery (*now as fine as 31 centimeters*), that permits the imagery analyst to provide very detailed analysis of a facility's infrastructure.*" [21] Finally, such imagery can be used to investigate alleged undeclared activities.

The analysis of both satellite-based and terrestrial imagery is playing an increasing role in IAEA State Evaluations. The IAEA first established an in-house Satellite Imagery Analysis Unit (SIAU) in 2001 to provide an independent capability within the Department of Safeguards for "*the exploitation of satellite imagery which involves imagery analysis, including correlation/fusion with other sources (open source, geospatial, and third party*"). [22]. The staff is proportionally small considering the workload, and it takes years of experience for analysts to gain proficiency, which can be difficult to acquire in-house given the IAEA's regular rotation

[114] Much of the information in this section was adapted from Frank V. Pabian, "Commercial Satellite Imagery: Another Tool in the Non-proliferation Verification and Monitoring Tool-Kit," a chapter in the Nuclear Safeguards and International Security textbook, Elsevier, June 1, 2008. http://www.elsevier.com/books/nuclear-safeguards-security-and-non-proliferation/doyle/978-0-7506-8673-0#description ; and F.V. Pabian, G. Renda, R. Jungwirth, L.K. Kim, E. Wolfart, G.G.M. Cojazzi, "Recent Developments Promoting Open-Source Geospatial Synergy: Emerging Trends and Their Impact for Nuclear Non-proliferation Analysis," Proceedings of the INMM-56th Annual Meeting, Indian Wells, California USA. July 12-16, 2015; and Frank V. Pabian, Guido Renda, Rainer Jungwirth, Lance K. Kim, Erik Wolfart, and Giacomo G.M. Cojazzi, "Commercial Satellite Imagery: an Evolving Tool in the Non-proliferation Verification and Monitoring Toolkit," to be published as a chapter in an upcoming Springer book entitled, "Risk and Information Driven Verification."

policy. The IAEA also draws heavily from expertise provided by member states in terms of personnel and nuclear infrastructure focused imagery analysis training. [23]

Recent Advances Make Commercial Satellite Imagery More Effective and Efficient

Since the year 2000, the quantity and quality of commercial satellite imagery has improved significantly. As an openly available information source, it is continuing to evolve as a result of significant improvements in temporal, spatial, and spectral resolutions from increasingly diverse and rapidly growing international satellite constellations. Commercial satellite imagery remains a critical verification technology that provides a non-intrusive capability to both follow-up on geospatial cueing information from other open sources and to remotely "peer over the fence" to obtain new and unique information from otherwise inaccessible or non-permissible environments anywhere on earth with a rapid revisit capability. The improving ("faster, better, cheaper") means of accessing this diversity of multi-sensor, multi-resolution imagery is providing increased opportunities for open source information augmentation and unexpected data-fusion synergies. Open source geospatial tools (e.g., Google Earth) continue to keep pace as efficient and cost-effective means to contextually visualize commercial satellite imagery in 3D as well as promote greater global transparency. This ongoing imagery (r)evolution continues to add to the expanding and transforming open-source toolkit to derive and assess new nuclear non-proliferation relevant information critical for enhanced global nuclear security. [24]

The number and variety of commercial imaging satellites that provide high-resolution imagery sufficient for monitoring and verification applications continues to grow. In early 2000, there was only one commercial imaging satellite, Ikonos, which was capable of providing electro-optical (EO) imagery at a resolution of less than two meters – the advent of one-meter resolution Ikonos imagery was heralded in a pioneering and milestone study [25]. Since then, the resolution of commercial satellite images has continued to improve, with the sharpest imagery currently available via WorldView-3 (and soon WorldView-4) at ~31 centimeters (cm). See Figure 2 As of this writing, there are approximately 30 earth orbiting commercial imaging satellites/systems with electro-optical spatial resolutions of two meters or finer.

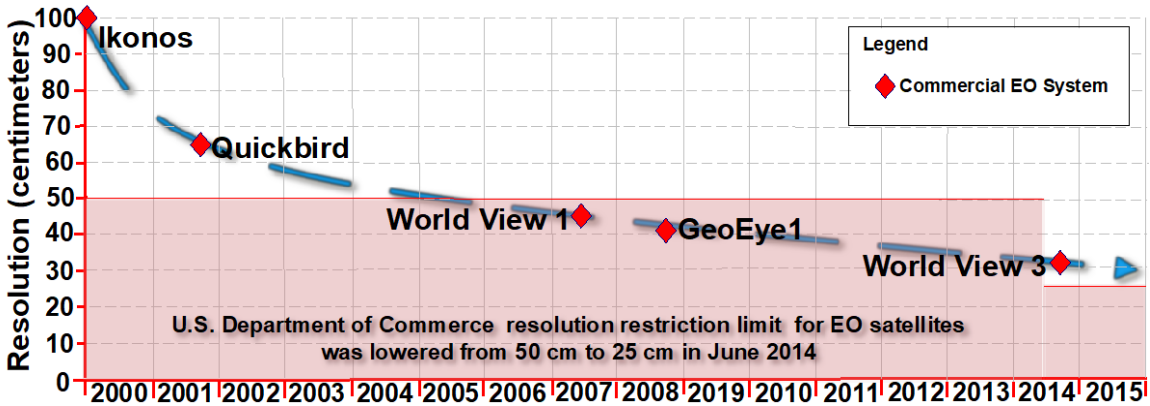

Figure 2: Benchmarks for increasingly fine resolution of commercial satellite imaging systems over time.

There has been a substantial consolidation of the commercial satellite imagery industry in the US over the past few years (DigitalGlobe merged with GeoEye, which itself had earlier merged with Orbimage). This has also been a period of greater market segmentation, with new imagery capabilities beginning to fill distinct market niches that may potentially benefit non-proliferation analysts.

New constellations of "refrigerator-sized" "small sats", "cubesats", and "shoebox-sized" "nano-sats" are now providing commercial satellite imagery with capabilities complementing those provided by the larger vendors

such as DigitalGlobe and Airbus Industries. [26] One US company, Terra Bella (formerly SkyBox recently acquired and renamed by Google [27][28]) is now operating three "small sats", known as SkySats 1, 2, and 3, by which it is acquiring 90 cm resolution color and near infrared imagery, providing new opportunities to augment data from existing higher resolution imaging constellations.[115] Terra Bella intends to acquire multiple images by multiple satellites of any point on Earth at several different times per day (or night) when tasked, eventually having as many as 24 satellites in its constellation. [29] Previous acquisition time windows had generally been limited to around 10:30 to 11:30 a.m. local time (although Digital Globe's WorldView-3 acquires imagery at around 1:30 p.m. local time). [30] Planet (formerly Planet Labs) has already placed 101 "nano-sats" into orbit, which although limited to three meters resolution, will be able to image the entire Earth every day. [31] The constellation will effectively provide, as the company claims, "*a line scanner for the planet*." [32] Urthecast is also in the process of creating its own free-flying satellite constellation of 16 satellites that is expected to provide frequent EO and EO video at ~50 cm, with near coincident radar imagery. [33]

Competition is increasing between various commercial satellite imagery vendors from the United States, France, India, Russia, China, Israel, Japan, the Republic of Korea, etc. Companies like the British Surrey Satellite Technology (SST) LTD, provide one-meter imaging capabilities for purchase on a turnkey basis. Three SST DMC-3 "mini-satellites" were successfully launched in 2015. [34] This competition could put downward pressure on prices, making commercial satellite imagery even more affordable. The diversity will also provide greater access to what might otherwise be denied areas with some vendors, and also ensure the integrity and validity of the data obtained for the historical record.

Temporal Resolution Improvements: Observing Activity

With such a large number of commercial imaging satellites and sensors orbiting the earth at one time (which one senior US Government official termed an "explosion" of geospatial information due in large part to the proliferation of small satellites [35]), the previous concerns, regarding temporal resolution or the timeliness of revisit between image acquisitions, will be less of an impediment with regard to monitoring and verification applications.

Commercial satellite coverage of the Chernobyl and Fukushima disasters shows how much has already changed in the past quarter century. For Chernobyl, commercial satellite images of 10 to 30 meters spatial resolution were taken days apart. [36] In monitoring Fukishima, DigitalGlobe not only acquired two ~50 cm spatial resolution images of the Fukishima reactor site on the same day (March 14, 2011, using two different satellites in its constellation), but those images were acquired one minute before, and only three minutes after, the building housing Reactor Unit 3 exploded. [37]. Advanced satellite capabilities in terms of pointing agility and telescopes' large aperture allow satellite imagery providers to be able to capture overhead images of one site multiple times per day, with – in exceptional circumstances - peak rates opportunities of several images in a few minutes.[116]

The introduction of full motion video (FMV) capabilities offers new advantages over single frame images in that it can allow more recognizable observation of plant operation signatures (e.g., rising cooling tower plumes) and other activity (vehicular and construction equipment movement) at sites of monitoring and

[115] https://directory.eoportal.org/web/eoportal/satellite-missions/s/skysat

[116] For example, DigitalGlobe managed to take "30 images over seven minutes" of the Galeao International Airport in Brazil (http://blog.digitalglobe.com/geospatial/real-technology-real-benefits-part-2-revisit-rate-collection-capacity/) and is regularly able to provide several images per days of any point of the globe: for instance Sydney, Australia, was imaged "over 40 times" between January and November 2015 (ibid.).

verification interest. The Terra Bella SkySat satellites can acquire such High Definition (HD) videos[117], with durations of up to 90 seconds, utilizing ~1.1meters spatial resolution sensors that are also capable of nighttime imagery (in one example, automobile headlights can be observed moving down the streets of Las Vegas, Nevada)[118]. The International Space Station (ISS) now also includes a one-meter resolution capable camera (operated by Urthecast), which can acquire 60 second long Ultra-High Definition (UHD) videos, over any location that the space station orbits.

One other aspect of this new era of observation satellites that should not be overlooked is that they are increasingly agile, providing another way to reduce the time gap (hence improve the spatial resolution) between multiple image captures. In one example, the same point was imaged three times on a single pass by the Airbus Industries' Pléiades 1B, supplying images at 70 cm resolution, which can be resampled at 50 cm. [119] While each image is only a snapshot in time, the gaps between each snapshot can be reduced, potentially capturing notable on-the-ground activity not otherwise possible.

This shortening time gap capability is bringing us ever closer to "persistent stare" on a global scale. Though varying in resolution from coarse to fine, "the types of spacecraft being developed by providers such as Terra Bella, UrtheCast, and Planet are intended to "darken the skies" with sensors. Their advantage is in their ability to revisit a target multiple times a day, offering more intelligence on the patterns of life and activities taking place there." [38] The more frequently any point on the globe is imaged (or videoed), the more difficult it becomes to conceal illicit operations. The resulting high repetitive revisit rate (from the sum of all the existing and planned EO systems) will also make it much easier to detect changes associated with the construction of larger features like roads and major buildings of potential relevance to monitoring and verification for non-proliferation applications. It should also become easier to detect such changes (for cueing) in an automated way using feature extraction tools (e.g., advanced machine learning algorithms) that are also currently under development[120]

Spatial Resolution Improvements: Seeing Greater Detail

Among the significant developments to have occurred since the beginning of the 21st Century included the public availability of one-meter resolution commercial satellite imagery (the first one-meter resolution images were provided by US commercial companies, allowed under a 1992 US federal law [39]). By 2008, 50 cm resolution imagery had become available via the GeoEye-1 satellite, and in 2014, 31cm imagery first became available via the WorldView-3 "superspectral" satellite.[121] Nine pixels at 30 cm resolution cover the equivalent footprint of one pixel at 90 cm, such that the resulting resolution actually represents a 9:1 improvement in image detail.

FigureFigure 3 helps one to more fully appreciate the significance of such improved resolution. What is particularly noteworthy is that it is now possible to distinguish between automobile types (e.g., sedans versus station wagons). This capability will lead to improved monitoring and verification of nuclear facilities (e.g., potentially allowing differentiation of different types of UF_6 cylinders in open storage (see lower section Figure 3), the identification of critical fuel cycle equipment either in transit or in open storage, or operational details associated with electrical power conditioning, and heating, ventilation, and cooling (HVAC) related equipment and infrastructure). The bottom images are of UF_6 cylinders. Lower right is aircraft derived, but is

[117] https://www.youtube.com/watch?v=fCrB1t8MncY
[118] http://www.skyboximaging.com/blog/Nighttime-HD-Satellite-Video
[119] Pleiades-HR (High-Resolution Optical Imaging Constellation of CNES) https://directory.eoportal.org/web/eoportal/satellite-missions/p/pleiades#foot33%29
[120] See for example, Descartes Labs, http://www.descarteslabs.com/
[121] a June 2014 change in US Federal law permitted US companies to sell satellite imagery with resolution as fine as 25 cm.

illustrative of what is possible at ~30 cm resolution. Such imagery is capable of revealing stiffening rings on large UF_6 cylinders that are critical for definitive identification.

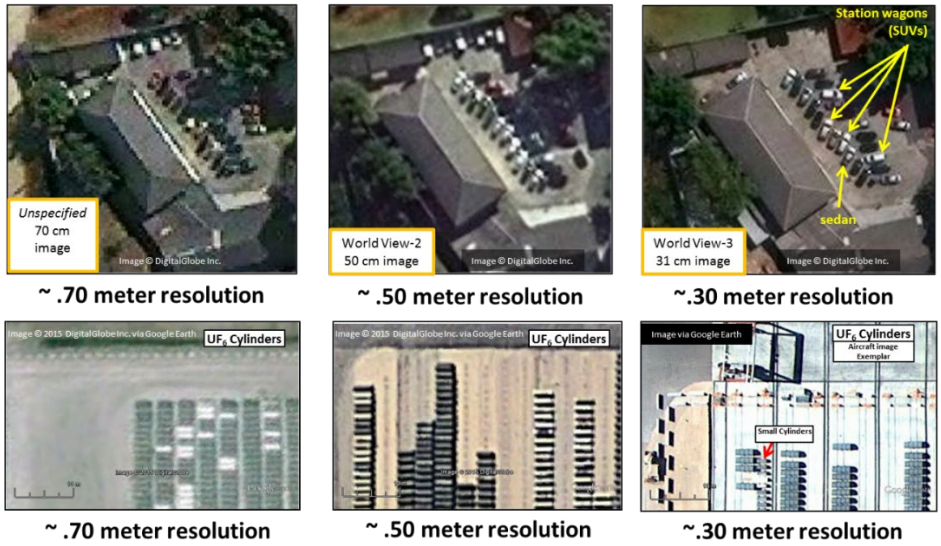

Figure 3: Interpretability comparison: the top images are exclusively from commercial imaging satellites over Sao Paolo, Brazil; but each was acquired on a different day [40].

Spectral Resolution Improvements: Seeing Beyond the Visible

To date, commercial satellite imagery which is being utilized for open-source non-proliferation and potential treaty verification applications has primarily involved electro-optical (EO) multi-spectral bands in the visible and near-infrared combined to create panchromatic sharpened naturally appearing color imagery. While it is not possible here to address all of the implications of applying other commercial satellite-based sensor suites to promote additional synergies, it is important to at least be aware of their complementary strengths that other sensors can add and that they are also evolving with improving resolutions.

Synthetic aperture radar (SAR) imagery, with resolutions now available down to ~25 cm[122], is not only useful for all hours, day or night, monitoring of activity, but it is particularly helpful in detecting security perimeters that might otherwise be obscured by vegetation. Radar imagery, from the European Union's Sentinel satellite, has also been used interferometrically to detect subtle non-visible surficial changes arising from an underground nuclear test for enhanced geo-location. [41] Hyperspectral imagery (as is currently available from the US Hyperion satellite[123], the European Space Agency's (ESA) Proba-1 satellite[124], and soon to be on the German EnMap satellite[125]) is derived from data covering up to hundreds of bands (at resolutions of between 17 and 34 meters) which can provide the capability to discriminate between materials and/or minerals, e.g., chalcopyrite (copper-iron-sulfide) versus hematite (iron oxide). Such a capability could play an important role in geologic mapping and where such minerals are reported as occurring, or are suspected of occurring, in association with uranium bearing minerals when assessing a suspect uranium mine or ore processing facility. DigitalGlobe's newest WorldView-3 satellite, advertised as "super-spectral" with 29-bands (including panchromatic 31 cm at nadir and multi-spectral 1.24 meter at nadir), may provide similar unique insights. The additional new 3.7 meter resolution shortwave infrared (SWIR) capability makes it possible to

[122] TerraSAR-X Image Products, Airbus Industries, http://www.geo-airbusds.com/en/5646-terrasar-x-image-products
[123] Hyperion, NASA, http://earthobservatory.nasa.gov/Features/EO1Tenth/page3.php
[124] CHRIS, ESA, https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/proba/instruments/chris
[125] http://www.enmap.org/

see through thick haze and smoke. [42] Such a capability might be requisite for detecting some critical equipment movement of verification relevance not otherwise apparent by alternative remote-sensing means.

Thermal (TIR), medium-wave (MWIR) and short-wave (SWIR) infrared satellite imagerscan potentially provide unique operational information when combined with other geospatial information. One new development in the field of satellite-based infrared imaging is that the South Korean operated satellite, KOMPSAT-3A,[126] was successfully launched in March 2015 and is now operational. The KOMPSAT-3A has a 5.5 meter resolution mid-wavelength infrared (MWIR) imaging sensor, operating in the 3.3-5.2 micron range, with a coincident capacity for acquiring a 55 cm EO imagery for cross-correlation. Most significantly, KOMPSAT-3A now provides significantly finer spatial resolution infrared imagery than both Landsat 8 (30m SWIR, 100m TIR – resampled at 30m)[127] and ASTER (30m SWIR, 90m TIR)[128], and that imagery can be also acquired at night. To what degree Korea Aerospace Research Institute (KARI)'s MWIR imagery will be applicable for non-proliferation monitoring and verification has yet to be proven, but it is expected that it should provide the capability to readily detect warm water effluents and more precisely locate "hotspots" arising from operations at a variety of nuclear-related facilities.[23]

Improvements in Accessibility and Pricing

Huge volumes of commercial satellite imagery are now being provided at little or no direct cost as currently found on the various virtual globes, which can also be accessed on smart phones today (albeit not necessarily with all the functionality available on a computer). Virtual Globes (AKA Digital Earths), including Google Earth, Here, Bing Maps, Esri's ArcGIS, and the new maps app for Windows 10, etc., provide the capability to synoptically view multi-resolution, three-dimensional, virtual representations of the earth and have created a new venue to "navigate through space and time" with very high resolution commercial satellite imagery (augmented in many areas by even higher resolution aircraft imagery). [43] Global transparency via overhead observation has become the new norm for a growing global cadre consisting of everyone and anyone having an interest in nuclear non-proliferation and arms control verification.

Interestingly, when Google Earth first came on the scene in 2005, one common complaint was that the imagery was often too old and out of date (or more recently, that did not represent "a perfect planetary mirror",[129] with the implication that separate imagery purchases would always be necessary for current imagery. However, in some cases, particularly in those areas of high media interest, including nuclear facilities in Iran and the Democratic People's Republic of Korea (DPRK), the imagery can sometimes be quite current. For example, eight different high-resolution commercial satellite images are archived in the Google Earth historical layer of the DPRK's Punggye-ri nuclear test site for the period between the January 1, 2013 and February 12, 2013, the date of the third identified under-ground nuclear test. Google Earth's historical layer view permits high-resolution visual inspection of each of those images in sequence.

The price of both acquisition and processing of imagery, which had been another major concern in the 1990s and early 2000s (in that individual frames of archived imagery originally cost about $3000-4000 a frame), has, in some, but not all, cases, dropped substantially such that archived imagery from DigitalGlobe (for example) can be purchased for as little as $350 for a 25 square kilometer area, or around $500 for a similar area special order request. One interesting development is a smart phone app (for both Android and iPhone) that makes possible the purchase of a one kilometer square area of some archived commercial satellite imagery (including SAR) from up to 36 satellites for as little as $10.[130] (see lower left inset in Figure 5). In

[126] https://directory.eoportal.org/web/eoportal/satellite-missions/k/kompsat-3a
[127] http://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/landsat-8/
[128] http://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/aster/
[129] https://imagehunter.apollomapping.com/
[130] http://www.spymesat.com/

April 2015, the ESA began providing SPOT and Pléiades data for free for research and application development through project proposals submitted via ESA's Earth Online Portal.[131]

Searching the multitude of available imaging archives of the increasingly diverse vendor options would have been a daunting task if not for the creation of web-based applications such as Apollo Mapping's Image Hunter[129] or Geo-Cento's Earth Images[132], which provide quick access to multiple image archives of different vendors from different countries. However, as of this writing, there is still not a complete "one-stop-shop" for all vendors of commercial satellite imagery, but may emerge if present trends continue.

With respect to hardware and software expenses, those costs have also dropped dramatically, and the large file sizes associated with such imagery are also much easier to transfer, process, and store than ever before. "In-the-cloud" storage and the processing of big data in a distributed environment across clusters of computers using simple programming models via open-source frameworks like Apache Hadoop, now empowers anyone, anywhere with previously unimagined, low cost computing power.[133]

Additionally, in 2015, Google Earth Pro (previously priced at $399) became freely downloadable. It offers the additional key benefits (not previously available with the original no-cost version) of allowing area measurements for facility size de-terminations; video movie-making of "fly-throughs" for pre-inspection familiarization, etc.; and the capability to create "view-sheds" to highlight all areas within a given line of sight to assess ground level building and terrain masking, etc., that might also be useful for safeguards pre-inspection planning.[134]

Imagery Analysis is Critical for Effective Use of Commercial Satellite Imagery

Imagery analysis is the extraction of meaningful information from images. In previous studies, it was stated that commercial satellite imagery, as it is available for purchase today in its raw form, is nothing more than "a pile of pixels". [44] As one practitioner has pointed out, "*Pixels are becoming a commodity, and the real value is in extracting that data, making it understandable, and making it useful to customers*,"[i] and "*Albert Einstein observed that information, however, is not knowledge. Raw data means nothing without interpretation.*"[ii]

An exemplar showing the timeliness, responsiveness, and global coordination that is now possible from the commercial satellite imaging community involves the attempt to locate and rescue two lost hikers in the Andes Mountains. TomNod[135] (Mongolian for "Big Eye"), sought and obtained commercial satellite imagery from DigitalGlobe, and within hours engaged nearly 800 globally-linked volunteers in the search. The imagery was not only made available within two days, but was of sufficient resolution (~50 cm) to see the lost and doomed hikers' footprint tracks in the snow. [45] And with regard to using "crowdsourcing" as an open source means to solve nonproliferation problems, one recent addition to the toolkit includes the experimental "Project on Crowdsourced Imagery Analysis," which is hosted by the James Martin Center for Nonproliferation Studies.[136] The goal is to enlist as many eyes, preferably expertly trained, onto specific areas of the world of nonproliferation concern, which may not have been correctly characterized to date. The various iterations in labeling would be instructive to non-experts as well.

[131] https://earth.esa.int/web/guest/pi-community/apply-for-data/3rd-party
[132] http://www.geocento.com/
[133] http://www.sas.com/en_us/insights/big-data/hadoop.html
[134] http://www.gearthblog.com/blog/archives/2015/02/google-earth-pro-viewshed-tool.html
[135] https://www.tomnod.com/
[136] http://www.geo4nonpro.org/

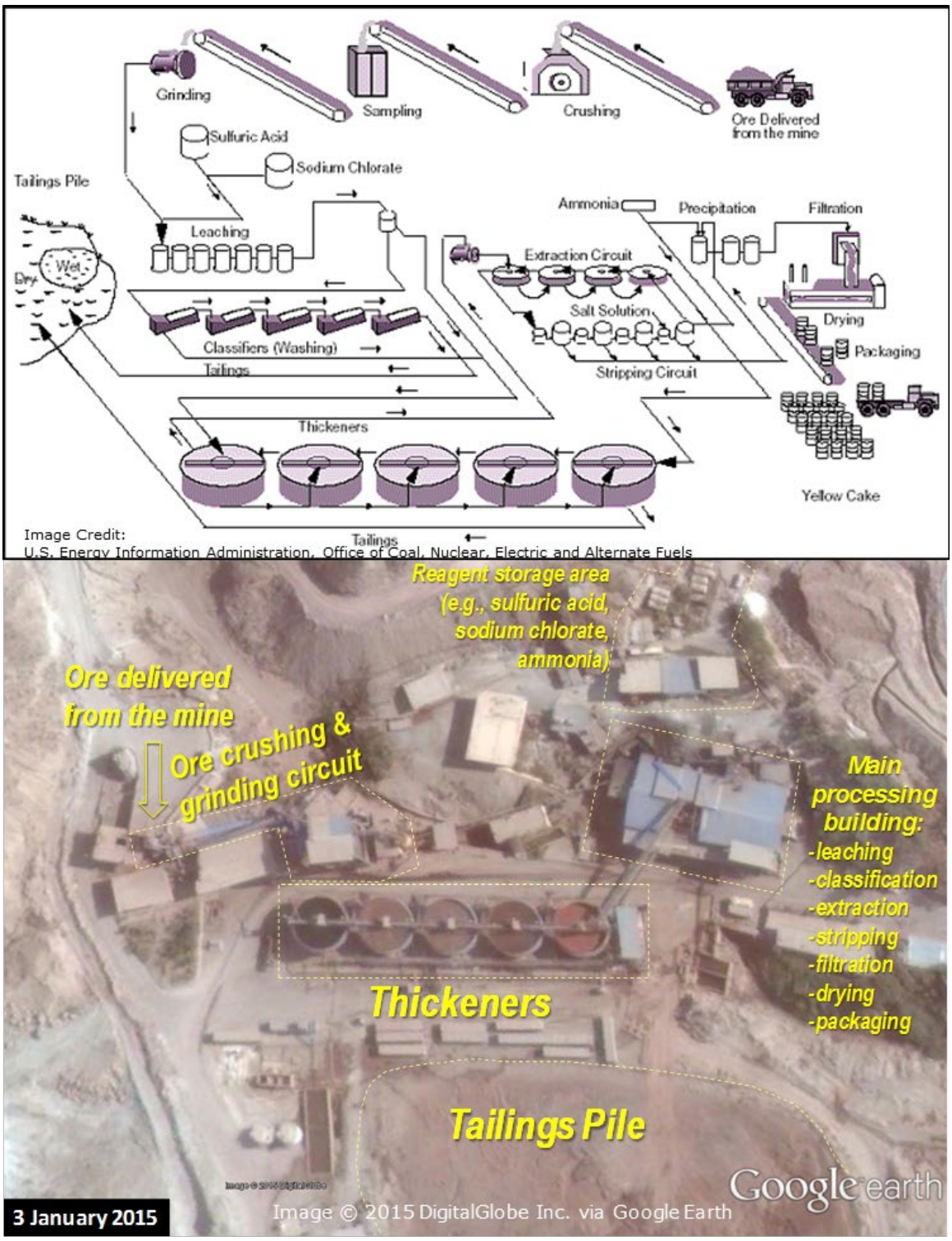

Figure 4: Signatures can play a critical role in nuclear fuel cycle infrastructure analysis. The top view provides a flow diagram of the key components in the operation of a uranium ore concentration plant. The lower image is an operational uranium ore concentration plant. However, such near perfect correlation with signatures is unusual and unlikely to be found in most other cases. Diagram credit: Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels.

Imagery analysis is the means by which a body of pixels is holistically interpreted, and creatively combined, in light of other open-source information (e.g., safeguards pertinent data) to synergistically derive new, "value-added," information from the raw un-annotated imagery. That information can then be added to the overall

existing body of knowledge with respect to a particular facility, activity, or program. Imagery analysis is critical to verification and monitoring, particularly as it applies to identifying possible clandestine "undeclared facilities and activities." Well-trained and experienced imagery analysts, who are fully cognizant of the nuclear fuel cycle and its infrastructure, equipment, and operations, and who are able to distinguish them from those associated with other industrial processes, must be the ones to competently interpret commercial satellite imagery.

IAEA imagery analysts have also noted that, "*Nuclear facilities are similar to industrial-type building complexes with multiple pipe connections, discharge and effluent management systems, complicated electrical networks, etc. The analysis of complex nuclear fuel cycle-related facilities requires a high level of detail that is best addressed with high resolution (<1m) imagery.*" [23]

Imagery analysts must also be acutely aware of the possibilities for deception and signature suppression. Not all observable facilities and equipment will exhibit the near perfect signature correlations as found in the infrastructure training exemplar shown in Figure 4.

The imagery analysis process is also heavily dependent on the eye of the beholder. John Jensen (2007) described factors that distinguish a superior imagery analyst. He said, "*It is a fact that some image analysts are superior to other image analysts because they: 1) understand the scientific principles better, 2) are more widely traveled and have seen many landscape objects and geographic areas, and/or 3) they can synthesize scientific principles and real-world knowledge to reach logical and correct conclusions. Thus, remote sensing image interpretation is both an art and a science.*" [46]

David Sandalow has similarly noted, "*Imagery interpretation can take considerable skill and training, and misinterpretation is not difficult. Without strong experience and training, it can be relatively easy to see proof of sinister intent in a benign image, or miss details that would be conclusive to a knowledgeable photo interpreter.*" [47] The possibility of misinterpretation, or discovering "false positives," can happen in the course of any imagery analysis for any purpose. With respect to nuclear non-proliferation, innocuous facilities can sometimes have the potential to be mistaken for undeclared nuclear facilities of interest for treaty monitoring and verification, particularly during early construction phases.[137] One example shows how the concrete foundation work located in a large, deep circular excavation that was observable in 2009 in an area north of Shiraz, Iran, exhibited some of the physical features that were somewhat similar to what had previously been observed during the early phase of construction of the IR-40 radioisotope production reactor located near Arak, Iran. [24] The building turned out to be a hotel.

Finally, some relevant tenets: 1) never assume that what can be discovered is already known, and 2) never assume that what can be discovered is not already known. One must do the requisite background research, using all available open sources, to verify each discovery, and to report and caveat that discovery at the most appropriate level of objective certainty.

[137] Adapted from the paper by F.V. Pabian, G. Renda, R. Jungwirth, L.K. Kim, E. Wolfart, G.G.M. Cojazzi, "Open Source Analysis in Support to Non-proliferation Monitoring and Verification Activities: Using the New Media to Derive Unknown New Information," IAEA: Symposium on International Safeguards: Linking Strategy, Implementation and People, vol. IAEA-CN-220, p. Page 320 - Paper n° #312, October 23, 2014.

Open Source Synergy: Creating Innovation in Verification Applications

This section highlights the utility of combining information from multiple open sources together with openly available commercial satellite imagery to derive unique synergy, such that the whole of the information that can be gleaned from the combination is really greater than the simple sum of the information from the multiple sources if each were to be viewed and analyzed in the absence of the others.

Example: Open Source Identification of the Pasmangoor Nuclear Waste Storage and Stabilization Facility in Iran[138]

This example illustrates how, through the use of open-source media cueing together with multiple images from multiple commercial satellites provided cost-free by Google Earth (along with a separately purchased image at low-cost) it was possible to newly locate, identify, and characterize a possible nuclear waste site by simply following-up on a single report from Iranian news [48].

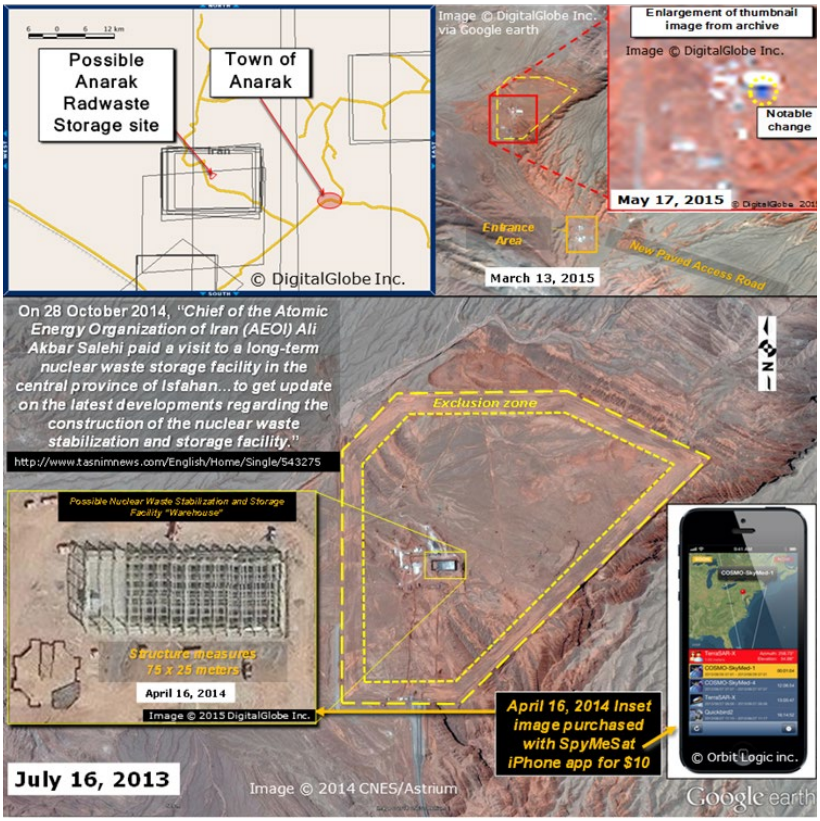

Figure 5: In following-up to a single news report (see quote in inset), with commercial satellite imagery it was possible to identify a new "Nuclear Waste Stabilization and Storage Facility" nearing completion near Anarak, Iran (33.364208 N, 053.467296 E). Significantly, the April 16, 2014 inset photo (bottom left), showing substantial concrete and steel construction, was purchased via SpyMeSat for $10 and was more recent than that currently found on Google Earth. Google Earth has since been updated to include most recent imagery from December 10, 2015. Iphone picture: Image © 2000-2014 Orbit Logic Inc. All Rights Reserved. Iphone picture source: http://www.orbitlogic.com/products/SpyMeSat.php.

[138] The example is also adapted from: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC97258/reqno_jrc97258_online%20version%20pdf.pdf, but includes entirely new and original analysis.

In late 2014, Iranian news reported that the, "*Chief of the Atomic Energy Organization of Iran (AEOI) Ali Akbar Salehi paid a visit to a long-term nuclear waste storage facility in the central province of Isfahan. Salehi visited the city of Anarak…to get update on the latest developments regarding the construction of the nuclear waste stabilization and storage facility.*" [48]. A simple search of the area around the town of Anarak, Iran, conducted via the most recent imagery available from Google Earth (July 16, 2013, , large bottom image), identified the location of a candidate site. A subsequent review of DigitalGlobe imagery archives (Figure 5) revealed multiple acquisitions centered on that same site, indicating that this site first began attracting continuing interest by others in early 2014 (although Google Earth shows that construction at the site was first underway by October 2011). The two then most recent images (Figure 5, top right, from March 13, 2015 and May 17, 2015) were viewable for free directly from those archives (albeit at reduced resolution). Even at the reduced resolutions, they were sufficient to show continued construction and changes onsite, e.g., like the addition of a new blue roof to a small building in close proximity to the largest building onsite. The overall site was found to be served by a newly paved access road and an outer entrance facility (Figure 5 top right), which exhibits the requisite features to include a secure storage vault-type radiological waste structure situated in dry, stable, geology that is also not susceptible to flash flooding.

Subsequent to the above analysis, in April 2016, Iranian television broadcast video from the ground photos and aerial drones as found on YouTube of a new radiological waste site which confirmed the identification of the site based solely on commercial satellite imagery. (See Figure 6) The radiological waste site is officially named the Pasmangoor Nuclear Waste Storage and Stabilization Facility in Anarak.[139]

Figure 6: The Pasmangoor Nuclear Waste Stabilization and Storage Facility near Anarak, Iran. The white-roofed building is the concrete vault radiological waste storage building.

[139] Please see: https://www.youtube.com/watch?v=YbzzVeXlVOA and https://www.youtube.com/watch?v=_FIsYR7IaiM

Those videos also provided interior views of the main storage vault building, with radioactive waste storage canisters shown being off-loaded from a delivery truck by an overhead crane and into one of the concrete vaults. (See Figure 7).

Figure 7: Interior views of the main concrete vault storage building as seen on an Iranian publicly posted video on YouTube.

Conclusions

Open source information, including commercial satellite imagery, has already been proven to be a timely and accurate means to support, supplement, and/or enhance nuclear and other non-proliferation related ongoing treaty monitoring and verification activities. Not only has it been supporting onsite inspection planning and monitoring and verification of declared activities, [49] [50] but, because of the accompanying global transparency, it also "*increases the possibility of detecting proscribed nuclear activities.*" [20] With technological advancement, a new era has begun with expanded new capabilities in earth observation that include large constellations of more agile and capable satellites having improved spatial, spectral, and temporal resolutions (that includes high definition video). Those capabilities are synergistic in that the sum of derivable information is greater, in aggregation, than the total of the information would otherwise be were the images viewed in isolation (see Figure 8). Commercial satellite imagery provides global coverage, and much of that imagery is freely available via digital virtual globes. Moreover, such freely available imagery is increasingly easy to supplement with focused additional imagery purchases from multiple platforms, with multiple sensors, from multiple companies, from multiple nations, and at least some can be purchased with only a smart phone for as little as ten US dollars. Such imagery will also continue to be an enabler of independent action, in that it democratizes the availability and use of the medium by anyone in the world with digital information technology access.

However, we must also be fully aware that such democratization provided by open sources also increases the potential for misinformation via deception, signature suppression, or simple human error in interpretation (and misinformation can easily "go viral"). As commercial satellite imagery capabilities and usage continue to

evolve, the consequences for future monitoring and verification efforts will only grow in significance. While neither a panacea nor stand-alone basis for any safeguards relevant conclusions, open sources, which include commercial satellite imagery, provide another means to augment other IAEA information in deriving such conclusions while also promoting greater global transparency.

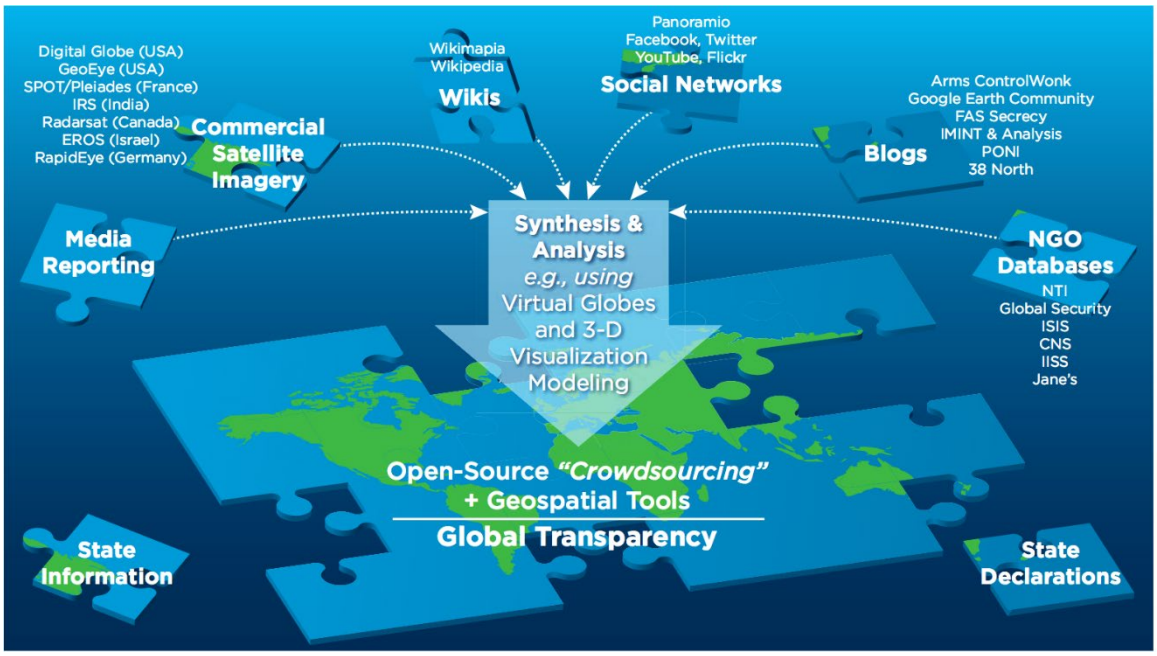

Figure 8: Open Sources, Commercial Satellite imagery, and Geospatial Tools Increase Global Transparency in the Service of Safeguards and Non-Proliferation Monitoring and Verification Applications. (Source: NTI [51]).

Finally, open source data is valuable to any agency or organization seeking a more complete and transparent picture of developments that fall under its purview. In recent testimony presented to the US Senate, the US National Geospatial Intelligence Agency Director, Robert Cardillo, said:

"Open content will be embraced with the same fervor as classified content, and in many cases, we will use open content first and augment with classified sources to reject, confirm, or increase confidence in analytic judgments." [38]

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ESARDA Course

The European Safeguards Research and Development Association (ESARDA) has set up since almost two decades a course on nuclear safeguards and non-proliferation, the so-called ESARDA Course. This is to fill in the gap of the generally missing education and training programs fully dedicated to nuclear safeguards and non-proliferation from curricula of universities or other E&T organizations. The course is recognised as optional course in the European curriculum for Nuclear Engineering with three credits in the European Credit Transfer System (ECTS). Its program includes lectures, group-exercises, cases-studies, visits to safeguards laboratories and a course evaluation. The course addresses various aspects of safeguards and non-proliferation such as:

- Regional and international legal framework
- Nuclear fuel cycle and its verification methodologies and technologies including statistics on accountancy and auditing
- State system of accounting for and control of nuclear material
- Management and analysis of information, such as those collected from open sources and export/import control.

This course is annually organized in Ispra (Italy) by the Nuclear Security Unit of the Joint Research Centre (JRC) under the training and Knowledge Management working group (TKM) of ESARDA. Due to Coronavirus pandemic, the course was cancelled in 2020 then organized on-line in 2021 and 2022. This full-week course is open to master's degree students, in particular in nuclear field, but also to international regulation and relation students as well as to young professionals in the field. This book presents the safeguards and nonproliferation topics dealt with in ESARDA Course.

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The ESARDA Course

For a period of almost two decades the European Safeguards Research and Development Association (ESARDA) has been organising a course on Nuclear Safeguards and Non-proliferation, the so-called ESARDA Course. The aim is to fill the gap of missing education and training programmes fully dedicated to Nuclear Safeguards and Non-Proliferation from the Curricula of universities or other E&T organisations. The course is recognised as optional in the European Curriculum for Nuclear Engineering with three credits in the European Credit Transfer System (ECTS). Its programme includes lectures, group-exercises, case-studies, visits to safeguards laboratories and a course evaluation. The course addresses various aspects of Safeguards and Non-Proliferation such as:

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